

The evaluation of five coated and non-coated grass species for the rehabilitation of gold and platinum mine tailings in South Africa

H Taute
21182019

Dissertation submitted in fulfilment of the requirements for the degree *Magister Scientiae* in *Environmental Sciences* at the Potchefstroom Campus of the North-West University

Supervisor: Prof K Kellner
Co-supervisor: Mr PW van Deventer

November 2016



ABSTRACT

H Taute, K Kellner & P van Deventer

Land use and, more recently, land rehabilitation has historically been, and remains, a key driver in the economic growth of South Africa. Environmental legislation as well as the involvement of all spheres of government and the private sector are key to the development and execution of successful rehabilitation and land use implementation action. This remains a strategic bargaining method for those in power as natural resources are directly linked to financial wealth in the current economic climate.

The value of land stretches beyond the financial realm – it includes different attributes, adds to each person’s life in a different way, and has a critical role in a sustainable ecosystem. Rehabilitation of degraded land therefore should not be a difficult choice, but a simple personal choice for each individual, but more importantly for mining houses and environmental government institutions as the principal guardians of our natural resources and a principal driver in the process of resource management. To ensure truly successful rehabilitation, scientific research has developed best-practice guidelines and methods to improve the chances of land use capability – for this study, especially in the post-mining landscape.

A major role during rehabilitation of gold and platinum mine tailings storage facilities (TSFs) is played by the vegetation established. To form a sustainably biodiverse ecological community, quality preparation of soil is critical, viable seed need to be sourced and environmental factors have to be minimised in some cases and maximised in other. AGT Foods Africa (Pty) Ltd (Krugersdorp, South Africa) is a major role player in the provision of quality seed (>80% viable) to the international market. They are innovative in the production of coated seed for improved performance in adverse climatic landscapes. These “enhanced” seed provide a variety of benefits such as improved seed handling, improved biomass in agricultural uses, seed protection against various factors and the availability of short-term microenvironment plant-available nutrients for each seed.

AGT Foods has been involved with research in conjunction with the North-West University since 2007 to better understand the impact of seed coating on germination and establishment of different species. The results obtained from these studies have allowed further research to take place and new ideas to come to the fore, which will ultimately empower rehabilitation specialists and the seed industry as a whole for the successful implementation of rehabilitation techniques in South Africa.

The objective of this study was to investigate and compare five coated and non-coated species, chosen from the results of previous studies, funded by AGT Foods, on gold and platinum mine TSFs under dryland conditions. Thereby consolidating previous results from laboratory and nursery research into practical attempts at best-practice rehabilitation techniques. The species were evaluated based on germination, growth and survival over two growth seasons and compared in terms of species frequency and population density combined with soil analysis over time.

The species chosen from previous studies were *Cynodon dactylon*, *Eragrostis curvula*, *E. tef*, *Medicago sativa* and *Sorghum* sp. (forage sorghum). All five species were sown onto gold and platinum tailings material on existing TSFs and monitored over two growth seasons after the soil had been ameliorated, as is common practice and required for successful establishment of vegetation in the rehabilitation industry. The seed were supplied by AGT Foods, who had tested the viability of each batch to be >80%. Some of the trials were left without mulch cover to ascertain the importance thereof when compared to mulch-covered plots.

In all of the trials, the seed germinated well and established successful vegetation stands over the two growth seasons. The plots left without mulch showed very little germination initially and were covered by opportunistic rye grass (possibly transported via the compost used) for the first growth season. Thereafter, the species mix sown for the research trial revived completely to outgrow some of the other established trials. This proved that viable seed remained in the seedbed and were able to germinate even after long periods of dormancy in acidic gold TSF material.

Coated *E. curvula* and *C. dactylon* performed better than non-coated seed of the same species in some cases; *M. sativa* and *Sorghum* sp. performed similarly between coated and non-coated trials. Perhaps what counted most in favour of

coated seed was the fact that non-coated seed contained approximately 50% more seed per kilogram than coated, but the performance of coated seed remained similar or slightly better than that of non-coated seed. Furthermore, interesting relationships between different species and soil nutrient availability were observed and created the opportunity for seed coating enhancement to be tailor-made for certain soil factors or locations.

Coated seed of *E. curvula*, *C. dactylon*, *E. tef*, *M. sativa* and *Sorghum* sp. are suitable for rehabilitation practices and, if sourced from a reputable seed producer, could improve the turnaround times for successful mine closure projects.

Keywords: coated seed, tailings storage facilities, successful rehabilitation, viability

UITTREKSEL

H Taute, K Kellner & P van Deventer

Grond gebruik, en meer onlangs grond rehabilitasie was histories, en bly tot vandag 'n hoof rolspeler in die ekonomies groei van Suid Afrika. Omgewings wetgewing, die betrokkenheid van elke regerings departement, sowel as die privaat sektor – is krities tot die ontwikkeling en uitvoering van suksesvolle rehabilitasie en grond gebruik. Dit bly n strategiese bedinging metode vir diegene in beheer, siende dat natuurlike hulpbronne direk verbind is aan finansiële welstand in ons huidige ekonomiese klimaat.

Die waarde van land strek verder as die finansiële terrein – die bevat verskillende kenmerke, dra by tot elke persoon se lewe op n verskillende manier en speel 'n kritiese rol in 'n volhoubare ekosisteem. Die rehabilitasie van gedegradeerde landskappe moet daarom nie 'n moeilike keuse wees nie, maar 'n eenvoudige en persoonlike keuse vir elke individu, en soveel meer vir myn instansies en regerings departemente bemoei met omgewings sake. Hierdie rolspelers bly krities, as die voog van ons natuurlike hulbronne en die volhoubare bestuur daarvan. Daarom, om suksesvolle rehabilitasie te verseker – het wetenskaplike navorsing - praktyk riglyne en metodes ontwikkel om die kansen van landskap gebruik te verbeter – in hierdie studie, spesifiek in die post-ontginning landskap.

Een van die hoof rolspelers gedurende die rehabilitasie van goud en platinum sliksdamme is die plantegroei wat gevestig word. Om n volhoubare, biodiverse ekologiese gemeenskap te vorm is die volgende aspekte van kritiese belang – voorbereiding van die groei medium, kiemkragtige saad moet verkry word en omgewings faktore en hul impakte moet ge-analiseer word om positiewe en negatiewe aspekte te verlaag of verhoog. AGT Foods Africa (Pty) Ltd (Krugersdorp, Suid Afrika) is 'n hoof rolspeler in die internasionale verskaffing van kwaliteit saad

(>80% kiemkragtig). Hul innoverende produksie van “omhulde” saad verskaf ’n reeks voordele soos verbeterde saad hantering, verhoogde biomassa vir landbou gebruike, saad beskerming teen ’n wye verskeidenheid faktore en die beskikbaarheid van ’n kort-termyn mikro-omgewing wat plant beskikbare voedingstowwe bevat.

AGT Foods is reeds vanaf 2007 betrokke by navorsing, saam met die NoordWes Universiteit, om die impak van omhulde saad op die ontkieming en vestiging van verskeie plant spesies te verstaan. Die resultate van hierdie studies het toegelaat dat verdere navorsing kon plaasvind en die vorming van nuwe idees na vore kon kom. Hierdie werk sal rehabilitasie spesialiste en die saad industrie bemagtig met wetenskaplike kennis om suksesvolle rehabilitasie tegnieke in Suid Afriak te verbeter en bevorder.

Die doel van hierdie studie spesifiek was om vyf omhulde en nie-omhulde gras spesies (gekies uit vorige studies en befonds deur AGT Foods) te bestudeer en vergelyk op goud en platinum sliksdamme (uitskot stoofasiliteite) onder droëland toestande. Daardeur word verseker dat die vorige werk uit laboratoriums en kwekerye saamgevat word in ’n praktiese aanslag op industrie riglyne vir myn rehabilitasie. Die spesies was ge-evalueer ten opsigte van ontkieming, groei en oorlewing oor twee groei seisoene en vergelyk in terme van spesie frekwensie en bevolkings digtheid gekombineer met grond analyses oor tyd.

Die spesies nagevors in hierdie studie is gekies uit resultate van vorige studies befonds deur AGT en sluit in *Cynodon dactylon*, *Eragrostis curvula*, *Eragrostis tef*, *Medicago sativa* en *Sorghum sp.* (voer sorghum). All vyf spesies is op goud en platinum sliks gesaai op bestaande sliksdamme (uitskot stoofasiliteite) en gemonitor oor twee groei seisoene nadat grond ameliorasie plaasgevind het soos algemeen hanteer in die rehabilitasie praktyk. Hierdie volgorde word aanvaar as krities vir suksesvolle rehabilitasie. Die saad is deur AGT Foods verskaf, en is getoets en goedgekeur as >80% kiemkragtig. Sommige van die proewe is sonder n deklaag gelaat om die belang daarvan vas te stel asook te kon vergelyk met ander proewe wat wel n deklaag ontvang het.

Die saad in al die proewe het suksesvol ontkiem en goed gevestig oor die twee groei seisoene. Aanvanklik was baie lae ontkieming sigbaar by proewe sonder n deklaag en het opportunisties rye gras (saad was moontlik vervoer in die kompos) die proewe heeltemal oorgeneem en bedek. Daarna het die spesie mengsel, wat gesaai was vir die proewe, heeltemal herstel en selfs beter resultate getoon as van die ander proewe waar rye gras nie teenwoordig was nie. Hierdie resultaat bewys dat kiemkrachtige saad in die saadbed kon aanbly en ontkiem na 'n lang tydperk van dormansie in suur goud slik.

Omhulde *E. curvula* en *C. dactylon* het beter gevaar as nie-omhulde saad van dieselfde spesie in sekere gevalle, *M.sativa* en *Sorghum sp.* het eenders gevaar tussen omhulde en nie-omhulde proewe. Die hoof voordeel van omhulde saad in hierdie proewe was die feit dat nie-omhulde saad ongeveer 50% meer saad per kilogram bevat as omhulde saad maar die vordering en prestasie van omhulde saad was eenders of selfs beter in sommige gevalle. Verder, interessante verhoudings tussen verskillende spesies en grond voedingstof beskikbaarheid is opgemerk en verskaf die moontlikheid vir die ontwikkeling van saad verbeterings vir spesie en grond spesifieke omstandighede.

Omhulde saad van *E. curvula*, *C.dactylon*, *E.tef*, *M.sativa* en *Sorghum sp.* is geskik vir myn rehabilitasie, en kan lei tot verbeterde omkeertye vir suksesvolle mynsluitings projekte - indien verkry van 'n betroubare bron.

Sleutelwoorde: omhulde saad, uitskot stoorfasiliteit, suksesvolle rehabilitasie, kiemkrachtigheid.

ACKNOWLEDGEMENTS

Ps 37: 3–4

“Trust in the LORD and do good, dwell in the land and enjoy safe pasture.

Take delight in the LORD, and he will give you the desires of your heart.”

I would like to thank the following persons and institutions for their contribution to the study:

Prof. Klaus Kellner, for his supervision, support and guidance as principal supervisor, for being hard when necessary and for imparting the wisdom gained over years of scientific guidance in Africa.

Mr Piet van Deventer, for his time and support in all matters relating to rehabilitation and practical experience gained from years of leading rehabilitation practice in South Africa.

Ms Leana Nel, who unfailingly and with a great heart always supported and assisted with the provision of seed, overall project support and for her role in the funding of this study.

AGT Foods Africa (Pty) Ltd for their support and funding, especially **Mr Brian Lever**.

Messrs SJ van Wyk and **Fanus Botha** of Agreeco Environmental Projects for allowing access to study areas and unfailing support and assistance.

Hannes, Kobus, Karel and **Neels** of Agreeco Environmental Projects, for assisting in logistics, labour provision and unwavering support and friendly guidance throughout the study.

Mr August Kruger for his assistance during my second year and for his friendship.

North-West University, Potchefstroom campus, for the use of facilities and equipment.

The technical assistance staff at the **School of Environmental Sciences (North-West University, Potchefstroom campus)** at various stages of the study.

EcoAnalytica Laboratories for soil sample analysis.

Mrs Esmé Harris for linguistic editing.

Fellow students, **Salmon van Rooyen, Jakkels Fouché** and **Abdullah Pelser** for constantly reminding me how much older I am than them, help in re-acquainting myself with university structures and general support and friendship.

My parents, for their unfailing love, support and belief in my abilities.

LIST OF TABLES

Table 1.1: World production of metal ores in million metric tonnes (MMT) (Cobb <i>et al.</i> , 2010).	3
Table 1.2: Cyanide-related mine accidents and environmental impacts as shown by Hilson and Monhemius (2005).	11
Table 1.3: Generally anticipated soil characteristics that could be problematic for vegetation covers on different tailings types (Van Deventer, 2008).	22
Table 1.4: Ecological monitoring criteria applicable to mine tailing storage facility (TSF) rehabilitation.	28
Table 3.1: Results and conclusions drawn by Brits (2007).	45
Table 3.2: Results and conclusions drawn by Westcott (2011).	48
Table 3.3: Results and conclusions drawn by Muller (2014).	50
Table 3.4: Results and conclusions drawn by Nel (2013).	52
Table 3.5: Critical results from the four studies.	53
Table 4.1: Study site global positioning system (GPS) coordinates.	56
Table 4.2: Description of trial plots at Paardekraal platinum mine tailings storage facility (TSF) and the North-West University (NWU) nursery. C: coated seed; NC: non-coated seed.	60
Table 4.3: Description of field trial plots at Crown and Rooikraal gold mine tailings storage facilities (TSFs). C: coated seed; NC: non-coated seed.	66
Table 4.4: Summary of field survey sites, methods and dates. TSF: tailings storage facility.	84

LIST OF FIGURES

Figure 1.1: Indication of soil water (volume) availability vs. soil texture fineness (Brady & Weil, 2008).	14
Figure 1.2: Plant-available nutrients range in comparison to different pH levels (Beegle, 2001).	18
Figure 1.3: Coated seed mix used in study field trial (Photo: H Taute, 2015).	29
Figure 1.4: Seed coating vs. pelleting, the two categories of seed coating (Zingel <i>et al.</i> , 2007).	30
Figure 1.5: Mining and decommissioning phases (Fourie & Brent, 2005)	31
Figure 4.1: Study site locations of gold (Crown and Rooikraal) and platinum (Paardekraal) mines in collaboration with Agreenco Environmental Projects.	55
Figure 4.2: Rustenburg historical rainfall and temperature data (10 year average) (www.worldweatheronline.com date of access: 12 June 2016)	59
Figure 4.3: Location and layout of the Bushveld Igneous complex with the location of the Paardekraal study site.	59
Figure 4.4: Field trial layout for Paardekraal platinum mine tailings storage facility (TSF) and layout for North-West University (NWU) greenhouse trials. C: coated seed; NC: non-coated seed.	60
Figure 4.5: Johannesburg historical rainfall and temperature data (10 year average) (www.worldweatheronline.com , date of access 12 June 2016).	63
Figure 4.6: Graphic illustration of the basins surrounding the Johannesburg.	64
Figure 4.7: Field trial layout for Crown and Rooikraal gold mine tailings storage facilities (TSFs) C: coated seed; NC: non-coated seed.	65
Figure 4.8: Nigel historical rainfall and temperature data (10-year average) (www.worldweatheronline.com , date of access 12 June 2016).	68

Figure 4.9: Timeline of study and sampling periods from February 2015 to August 2016 as well as periods of rehabilitation and amelioration activities.	77
Figure 4.10: Monthly average temperatures (°C) for the three field trial locations from October 2014 to October 2015. TSF: tailings storage facility.	78
Figure 4.11: Monthly average temperatures (°C) for the three field trial locations from November 2015 to May 2016. TSF: tailings storage facility.	79
Figure 4.12: Monthly average precipitation (mm) for the three field trial locations from October 2014 to October 2015. TSF: tailings storage facility.	79
Figure 4.13: Monthly average precipitation (mm) for the three field trial locations from November 2015 to May 2016. TSF: tailings storage facility.	80
Figure 4.14: Comparison of the total precipitation (mm) at each trial location. TSF: tailings storage facility.	80
Figure 4.15: Mine tailings storage facility side view. Field trials were established on slope and flat surfaces.	81
Figure 4.16. Density and frequency surveys through subjective placement of transects and quadrants in each plot (Photo: H Taute 2016).	82
Figure 4.17: Slope plots survey method at all trials.	83
Figure 4.18: Flat plots survey method at all trials.	83
Figure 5.1: Viable seed/m ² for coated and non-coated seed of <i>Eragrostis curvula</i> , <i>Cynodon dactylon</i> , <i>Medicago sativa</i> and <i>Sorghum</i> sp.	86
Figure 5.2: Comparison of the number of plants at Crown gold tailings storage facility slope plots (coated (C) vs. non-coated (NC) seed frequency) in 2015 and 2016 for <i>Cynodon dactylon</i> , <i>Eragrostis curvula</i> , <i>E. tef</i> and <i>M. sativa</i> .	88

Figure 5.3: Comparison of the number of plants at Crown gold tailings storage facility flat plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for <i>Cynodon dactylon</i> , <i>Eragrostis curvula</i> , <i>E. Sorghum sp.</i> and <i>M. sativa</i> .	88
Figure 5.4: Comparison of the number of plants at Rooikraal gold tailings storage facility slope plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for <i>Cynodon dactylon</i> , <i>Eragrostis curvula</i> , <i>M. sativa</i> and <i>Sorghum sp.</i>	89
Figure 5.5: Comparison of the number of plants at Rooikraal gold tailings storage facility slope flat plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for <i>Cynodon dactylon</i> , <i>Eragrostis curvula</i> , <i>M. sativa</i> and <i>Sorghum sp.</i>	90
Figure 5.6: Rooikraal TSF pre-amelioration and seeding (Photo: H Taute, February 2015).	91
Figure 5.7: Rooikraal TSF first survey for germination results (Photo: H Taute, April 2015).	91
Figure 5.8: Rooikraal TSF second survey for growth and survival results (Photo: H Taute, August 2015); damage due to tailings spillage indicated by the arrow.	92
Figure 5.9: Rooikraal TSF final survey for survival and progeny seed growth. (Photo: H Taute, August 2016).	92
Figure 5.10: Comparison of the number of plants at the platinum tailings storage facility plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for <i>Cynodon dactylon</i> , <i>Eragrostis curvula</i> , <i>M. sativa</i> and <i>Sorghum sp.</i>	94
Figure 5.11: Density comparisons between coated (C) and non-coated (NC) seed in slope plots at Crown gold tailings storage facility (2015–2016). □ <i>Cynodon dactylon</i> ; □ <i>Eragrostis curvula</i> ; □ <i>E. tef</i> ; □ <i>Medicago sativa</i> .	96
Figure 5.12: Density comparisons between coated (C) and non-coated (NC) seed in flat plots at Crown gold tailings storage facility (2015–2016). □ <i>Cynodon dactylon</i> ; □ <i>Eragrostis curvula</i> ; □ <i>Lolium multiflorum</i> ; □ <i>Medicago sativa</i> ; □ <i>Sorghum sp.</i>	97

Figure 5.13: Density comparisons between coated (C) and non-coated (NC) seed in slope plots at Rooikraal gold tailings storage facility (2015–2016). □ <i>Cynodon dactylon</i> ; □ <i>Eragrostis curvula</i> ; □ <i>Medicago sativa</i> ; □ <i>Sorghum</i> sp.	99
Figure 5.14: Density comparisons between coated (C) and non-coated (NC) seed in flat plots at Rooikraal gold tailings storage facility (2015–2016). □ <i>Cynodon dactylon</i> ; □ <i>Eragrostis curvula</i> ; □ <i>Medicago sativa</i> ; □ <i>Sorghum</i> sp.	100
Figure 5.15: Density comparisons between coated (C) and non-coated (NC) seed in slope plots at Paardekraal platinum tailings storage facility (2015). □ <i>Cynodon dactylon</i> ; □ <i>Eragrostis curvula</i> ; □ <i>Medicago sativa</i> ; □ <i>Sorghum</i> sp.	101
Figure 5.16: Density comparisons between coated (C) and non-coated (NC) seed in plots at the North-West University nursery (platinum tailings material) (2016). □ <i>Cynodon dactylon</i> ; □ <i>Eragrostis curvula</i> ; □ <i>Medicago sativa</i> ; □ <i>Sorghum</i> sp.	102
Figure 5.17: Crown gold tailings storage facility – cation exchange capacity (CEC) in relation to coated and non-coated plots (2015 and 2016).	104
Figure 5.18: Crown gold tailings storage facility – macronutrient availability in relation to coated and non-coated plots (2015 and 2016).	105
Figure 5.19: Crown gold tailings storage facility – micronutrient availability in relation to coated and non-coated plots (2015 and 2016).	106
Figure 5.20: Crown gold tailings storage facility – nutrient status availability in relation to coated and non-coated plots (2015 and 2016).	107
Figure 5.21: Crown gold tailings storage facility – particle size distribution in relation to coated and non-coated plots (2015 and 2016).	108
Figure 5.22: Rooikraal gold tailings storage facility – cation exchange capacity (CEC) in relation to coated and non-coated plots (2015 and 2016).	109

Figure 5.23: Rooikraal gold tailings storage facility – macronutrient availability in relation to coated and non-coated plots (2015 and 2016).	110
Figure 5.24: Rooikraal gold tailings storage facility – micronutrient availability in relation to coated and non-coated plots (2015 and 2016).	111
Figure 5.25: Rooikraal gold tailings storage facility – nutrient status availability in relation to coated and non-coated plots (2015 and 2016).	112
Figure 5.26: Rooikraal gold tailings storage facility – particle size distribution in relation to coated and non-coated plots (2015 and 2016).	113

LIST OF APPENDICES

Appendix A – Soil sample analysis reports, as received from the laboratories of EcoAnalytica.

Appendix B – Germination reports of trial species as received from AGT Foods Africa (Pty) Ltd.

Table of Contents

ABSTRACT.....	i
UITTREKSEL	iv
ACKNOWLEDGEMENTS.....	vii
LIST OF TABLES.....	ix
LIST OF FIGURES.....	xi
LIST OF APPENDICES	xvi
Chapter 1.....	1
Literature review.....	1
1.1 The history of rehabilitation in South Africa.....	1
1.2 Legislation	4
1.3 The rehabilitation process	7
1.3.1 Pre-rehabilitation phase	7
1.4 The impact of certain minerals on the environment.....	9
1.5 The impact of gold mining on the environment	11
1.6 The impact of platinum mining on the environment.....	15
1.7 Industry-related rehabilitation technology for gold and platinum TSFs.....	16
1.7.1 The critical role of plant nutrient availability.....	17
1.7.2 Functions of plant nutrients.....	18
1.8 Rehabilitation.....	20
1.8.1 Re-vegetation and biodiversity re-establishment.....	20
1.8.2 Biodiversity offsets.....	22
1.9 Conventional methods.....	23
1.10 Phytoremediation	24
1.11 Advanced methods to increase seed survival.....	25
1.11.1 Re-seeding of disturbed environments	26
1.12 Seed coating.....	28
1.13. Policy and legislation – mining operation and maintenance.....	30
1.13.1 Mining exploration.....	32
1.13.2 Mining and milling	32
1.13.3. Smelting and refining	32
1.13.4 Mine closure	32
Chapter 2.....	37
Project overview	37

2.1 Background of study	37
2.2 Project overview and objectives	38
2.3 General objectives	39
2.4 Specific objectives.....	39
2.5 Dissertation structure and content.....	40
Chapter 3.....	41
Review and summary of previous research.....	41
3.1 General.....	41
3.2 Research objectives of previous research projects	42
3.2.1. Brits (2007).....	42
3.2.2. Westcott (2011)	43
3.2.3 Muller (2014)	43
3.2.4 Nel (2013).....	44
3.3 Results.....	45
Table 3.2: Results and conclusions drawn by Westcott (2011).	48
Table 3.3: Results and conclusions drawn by Muller (2014).	50
Table 3.4: Results and conclusions drawn by Nel (2013).....	52
3.4 Summary of all results	53
Chapter 4.....	55
Materials and methods.....	55
4.1 Study site location.....	55
4.2 Rustenburg (Paardekraal TSF).....	56
4.2.1 Trial location	56
4.2.2 Vegetation.....	56
4.2.3 Climate	57
4.2.4 Historical average rainfall and temperature.....	57
4.2.5 Geology and soil.....	59
4.2.6 Trial layout and plot description.....	60
4.3 Johannesburg (Crown TSF).....	61
4.3.1 Trial location	61
4.3.2 Vegetation.....	61
4.3.3 Climate	62
4.3.4 Historical average rainfall and temperature.....	62
4.3.5 General description of geology and soil (Crown and Rooikraal TSFs).	63

4.3.6 Trial layout and plot description (Crown and Rooikraal TSFs)	65
4.4 Nigel (Rooikraal TSF)	66
4.4.1 Trial location	66
4.4.2 Vegetation.....	67
4.4.3 Climate	67
4.4.4 Historical average rainfall and temperature.....	67
4.4.5 Geology and soil.....	68
4.5 Study site rehabilitation procedures.....	69
4.5.1 Location and availability of workforce and machinery	69
4.5.2 Available ameliorants.....	69
4.5.3 Topography	71
4.5.4 Trials on slope areas – Mooifontein and Rooikraal gold tailings storage facilities.....	71
4.6 Study site soil sampling.....	72
5. Trial site methodology	73
6. Study sites – rainfall and temperature	77
7 Experimental design and layout of field trials	81
8. Monitoring of field trials	82
Chapter 5.....	85
Results and discussion	85
5.1 Introduction	85
5.2 Field trials.....	85
5.2.1 Frequency.....	86
5.2.2 Density	94
5.3 Soil analysis	102
5.3.1 Crown gold TSF redundancy analysis results	103
5.3.2 Rooikraal gold TSF redundancy analysis results	109
5.3.3 Paardekraal and North-West University (nursery) platinum TSF redundancy analysis results.....	113
5.4 Comparison of the soils at the Crown and Rooikraal TSFs	113
Chapter 6.....	115
Conclusion and recommendations	115
6.1 Introduction	115
6.2 Germination and establishment	116
6.3 Soil amelioration	118

6.4 General concluding remarks	119
6.5 Recommendations	119
Chapter 7	122
References	122
Appendix A	138
Appendix B	142

Chapter 1

Literature review

1.1 The history of rehabilitation in South Africa

Mining in South Africa started as early as the 1800s with copper mines recorded as the first mines in the Namaqualand on the farm Springbokfontein (later becoming the town Springbok) (Cairncross, 2006). Ever since, mining has grown to replace agriculture as the main contributor to infrastructure development and economic growth of South Africa (Ngcofe & Cole, 2014). Reichardt (2012) states that gold mining commenced during this time on the Witwatersrand but grew to cover areas in the East Rand and West Rand (Gauteng province), Welkom (Free State province) and Klerksdorp (North-West province). Early mining technology allowed gold mining through the sinking of shafts by way of blasting to recover the ore body underground. Stamp mills were used to crush ore and extract gold, but when un-oxidised, sulfidic ores were encountered, rotating cylindrical mills were developed, which crushed ore much finer and produced a product with a silt percentage of 75%. This “slime” was pumped on what we know today as mine tailings storage facilities (TSFs), also known as “mine dumps” or “tailing dams”. TSF types differ according to the type of ore mined and the physical and chemical methods used for extraction. The most common problematic elements that occur in TSFs are arsenic, barite, calcite, cyanide, fluorite, mercury, pyrite and quartz (Weiersbye & Witkowski, 1998).

The discovery of minerals in South Africa continued, e.g. diamonds were found near Kimberley in 1867 and gold on the Witwatersrand in 1886. South Africa’s mineral wealth increased dramatically in the following years. It is reported that in 2005, 55 different minerals were being sourced from 1113 mines and/or quarries within the borders of South Africa and that these minerals were mainly exported to generate 8% of the country’s gross domestic product (Sarsby & Meggyes, 2010).

Most of the mining today occurs in the provinces of Gauteng, North-West, Free State, Northern Cape and Mpumalanga (Ngcofe & Cole, 2014). In the Witwatersrand alone, approximately 400 square kilometres are covered by mine TSFs and consist

of 6 billion tonnes of gold and uranium tailings. Furthermore, the rate of waste production is increasing steadily (gold mining produces 105 million tonnes per annum) as new ore bodies are discovered and production operations increase to produce and extract maximum quantities of the accessible mineral (Mucina & Rutherford, 2006). If these figures are compared to those in Table 1.2, it can be seen that the rehabilitation of mine TSFs is a global issue due to the scale of operation as well as future mining operations.

During the early 1900s, mining and the placement of TSFs was not considered a major threat to the environment as no legislation had been promulgated regarding mine waste. Little was known about the effects on ecosystems in close contact with these waste areas. Additionally, space was abundant and, therefore, the adage “out of sight, out of mind” became apparent in the methods used in dealing with TSFs (Reichardt, 2012).

As industrial areas and settlements/towns started to grow, space constraints with regards to TSFs developed and there was a growing concern for the safety of surrounding communities. Issues such as water and wind erosion aggravated the circumstances surrounding TSFs in proximity to the settlement /towns. This led to complaints from communities in terms of dust pollution and health concerns (DEAT, 2005). The first legislation for the standardisation for mine tailing construction was published in the 1950s but only in 1970 was “surface protection” mentioned in Government Notice R922. In 1980 only, did rehabilitation appear in GN R537 (Hartzer 2009). As shown by Gonzalez (2005), health concerns in Mexico due to wind pollution were becoming evident. High levels of arsenic and lead were identified in hair and blood samples of children in the areas adjacent to major mining areas, which totalled a 6.552 million metric tonnes of waste and 2.36 million metric tonnes from only two mines that were used during this survey. Davies and Mundalamo (2010) indicate that health concerns over the dispersion of mine-related dust particles should be considered a major threat to communities in South Africa. Uranium, as an example, remains in tailings materials for up to 80000 years Davies and Mundalamo (2010). Uranium dust particles contain radionuclides, which are spread through wind to surrounding areas, impacting inhabitants and water sources. These particles can cause lung cancer, genetic mutations and, in some cases, mental retardation at high level exposure. Other minerals mined in South Africa that

could have health implications for miners or nearby inhabitants include copper, fluorine, iron, lead, manganese and zinc. Due to pollution by these substances, many mines have had to close and where mines still exist; the security and health legislation have become much stricter.

As shown in Table 1.2, the scale of ore production in the world in 1993 demonstrates to what extent mining contributed to pollution and why the rehabilitation mine TSFs intensified.

Table 1.1: World production of metal ores in million metric tonnes (MMT) (Cobb *et al.*, 2010).

Metal ore	Gross weight of ore (MMT)	Metal content %	Net weight of metal (MMT)	Mine and mill waste (MMT)
Aluminium	106	19	19.8	86
Chromium	10	30	3.0	7
Copper	>2500	0.4	9.4	>2490
Gold	≈466	0.0005	0.002	≈466
Iron	989	52	517.0	472
Lead	>45	6.5	2.9	>42
Manganese	22	33	7.2	15
Nickel	>130	0.7	0.9	>129
Platinum group	≈50	0.0005	0.0002	≈50
Uranium (1978)	1900	0.002	0.04	1900
Zinc	>219	3.2	6.9	>212

The effect of pollution through the uptake of harmful minerals by crops such as beans, lettuce, maize and tomatoes lead to in-depth studies about the health hazards caused by dust associated with mine TSFs. This prompted more studies on how rehabilitation is approached and carried out today. According to Raskin *et al.* (2006), phytoremediation has become a topic of discussion and research was initiated to study the capabilities of plants to extract from or render harmful minerals safe (e.g. metal trace elements) in different mediums and pollutants in soil and water. This has led to legislation and policies for the rehabilitation of mining areas (Cobb *et al.*, 2000). Plants were used in the uptake harmful minerals/metals, but the challenge was to establish vegetation on mine TSFs by supplying of the correct amounts of nutrients required for survival, especially where the provision of food is a

priority. However, many elements that are present in TSFs are also toxic to the growth and establishment of plants used for rehabilitation purposes. These include excessive amounts of calcium, copper, iron, magnesium, nitrogen, phosphorus, potassium, selenium, sodium and zinc, especially in gold mine TSFs of the Witwatersrand as indicated by Weiersbye *et al.* (1999).

By considering the importance of sustainable ecosystems and their role in the economy of South Africa, a response can be initiated towards impacted/degraded land by using economic value to quantify its importance. This serves as a starting point to understand the value of the ecosystems being lost as well as the necessary mitigation strategies to be considered for their rehabilitation. Sixty per cent of the world's surface is managed by humans and 60% thereof is for agricultural use. This leads to a further deduction that approximately a third of the world's arable land has already been impacted by degradation and desertification (ELD, 2015). The Economics of Land Degradation (ELD) Initiative reported in 2015 that the value of land lost due to degradation and desertification is 6.3–10.6 trillion USD globally. This indicates the necessity of proactive engagement and change in terms of global vision regarding rehabilitation/restoration resulting from the impacts of mining activities on the remaining available arable and natural ecosystems.

1.2 Legislation

Before the current strict legislation for the rehabilitation of TSFs was published by the Department of Minerals and Resources (MPRDA, 2002), several attempts have been made to reduce the health risks caused by wind and water pollution from TSFs. Attempts included the use of various methods such as rock cladding or topsoil material from adjacent areas to cover TSFs. One of the most popular methods was the spraying of sewage sludge as it was consistently available and contains ample nutrients (Ngcofe & Cole, 2014).

Even though this standardisation led to improved safety in terms of the construction of TSFs, research was still being undertaken to establish a best-practice rehabilitation technique, including rehabilitation via vegetation (Reichardt, 2012). Many studies were carried out to identify the most suitable plant species that can be used in the rehabilitation of different mine tailings materials, as the mineral content,

pH and texture of these materials differ depending on the ore that has been mined, as well as the region where the mines are located due to differences in climatic and geographic conditions. Rehabilitation by vegetation establishment was seen as a good solution to stabilise the often steep slopes of TSFs to mainly control wind and water erosion and pollution.

Because of legislation, such as the Constitution of South Africa (1996), the National Environmental Management Act 107 of 1998 (NEMA), the Mineral and Petroleum Resources Development Act 28 of 2002, the National Environmental Management Biodiversity Act 10 of 2004 and the National Environmental Air Quality Act 39 of 2004, mining companies are forced to follow strict legislation regarding the rehabilitation requirements of TSFs.

According to Bradshaw (1998), the impacts of mining on the environment can be considered a historical issue with some attempts at mitigation over time. Historically, these attempts have mostly been unsuccessful and underfunded. As stated above, this has drastically changed because of environmental legislation requiring strict requirements and international research to ensure best-practice mine rehabilitation efforts. As shown by Haagner (2008) and supported by the Society for Ecological Restoration Primer (2004), rehabilitating a TSF is a multi-faceted process that requires clearly defined goals and objectives to enable a successful ultimate outcome. Emphasis has been placed on long-term quantitative monitoring to attain good data of, for example, species richness and basal cover to select the correct species in the rehabilitation process. Evaluation should not be done qualitatively through observations only (Ruiz-Jaen & Aide, 2005).

Bradshaw (1998) further states that successful rehabilitation can only be achieved if the biological and chemical environment found on TSFs is optimised for the germination, establishment and growth of vegetation. The initiation of any rehabilitation technique on TSFs should therefore start with remediation of the soil to create optimal biogeochemical conditions for vegetation establishment and growth. This is supported by the South African Guidelines for Environmental Protection (South Africa, 1979), which states that the most successful outcome of a rehabilitation effort is to combine chemical soil amelioration and vegetation establishment. The purpose and objectives of rehabilitation should also be measured

by the efficiency with which ecosystem functions are reached. The use of landscape function analysis (LFA) has recently been adopted as a monitoring tool for the assessment of ecosystem function and for TSF rehabilitation monitoring (Haagner, 2008). LFA evaluates the biophysical value and operation of an ecosystem through visually observed soil surface indicators (Tongway & Hindley, 2004).

“Rehabilitation differs from the narrower definition of restoration by not aspiring to fully replace all of the original components of an ecosystem” (EPA Primer, 2006). The main difference between these concepts, as used in this dissertation, is that restoration attempts to restore an impacted area to its natural state (pre-impact condition) as opposed to rehabilitation, where it is acknowledged that an impact has occurred that has altered the soil, microbial, mineral and biological components to such an extent as to exclude it from any “natural” system that could be restored to its previous state (EPA Primer, 2006). The species composition of the surrounding biome occurring in a “natural” state is used to identify vegetation that is adapted to survive under the climatic and geographic conditions characterising a particular region.

The roll-on effects of industry and mining is not only the disturbance of the natural vegetation, soil and animal life on the TSF footprint itself, but have far-reaching effects on biodiversity and environmental goods and services. Environmental goods and services exist in a balanced system with inter-related functions and capabilities. To influence or remove a function is to influence the entire system, in some cases even destroying the capability of such a system by creating gaps in the “chain” (Schwartz *et al.*, 1999). Mining specifically adds extreme variables to these fragile ecosystems. Some of the impacts include acid rock drainage (ARD), heavy metal water pollution and salinization of soils and their effects are exponentially increased by the steep slopes of a TSF (Tarras-Wahlberg *et al.* 2001). The latter also contributes to increased wind speeds, leading to dust pollution, wind and water erosion, low water infiltration rates and overall impairment of root development due to loose soils and compacted soil layers. As shown by Weiersbye (2007), these external influences on vegetation establishment differ from site to site and are rarely found under natural conditions, emphasising the importance of selecting locally adapted indigenous plant species for the rehabilitation of TSFs, with the added

benefit of complying with the national environmental legislation as mentioned above (Mendez & Maier, 2008; Westcott, 2011; Muller, 2014).

1.3 The rehabilitation process

The rehabilitation of TSFs includes major financial-, resource- and time-related planning (Laurence, 2011). For successful rehabilitation to occur within a mine's lifetime, concurrent rehabilitation processes are considered the best approach to allow for sufficient time for vegetation establishment and the control of negative impacts, such as soil condition changes, erosion and pollution. The South African Chamber of Mines (2007) released a detailed document (Guidelines for the rehabilitation of mined land) regarding the different stages of rehabilitation and options for vegetation establishment or situations related to closure. The overall reasons for TSF rehabilitation in South Africa are to ensure ecological stabilisation of areas where the initial land use has been disturbed. In most mine rehabilitation plans and environmental impact assessment (EIA) requirements, the area should be rehabilitated to the initial land use after the mining operation has ceased. This emphasises that long-term quantitative monitoring procedures are needed, especially if vegetation is used in the rehabilitation process.

The following rehabilitation methods are described and used widely as best practices, dependent on the availability of materials, and budget and legal requirements. The main phases of the methods include the following:

1.3.1 Pre-rehabilitation phase

The technical objectives for rehabilitation are considered to be surface stability, minimisation of surface water and air pollution, prevention of soil and groundwater contamination, minimisation of visual impacts associated therewith and restoration ecosystems prior to obtaining mine closure (Mchaina, 2001). The methods to obtain these objectives are discussed below to illustrate the planning and other critical components of successful rehabilitation.

1.3.1.1. Soil stockpiling and cover

The use of the topsoil remains one of the most important factors for successful rehabilitation (Carrick & Kruger, 2007). Topsoil is defined by the Oxford Dictionary (2010) as the “cultivable surface layer of the soil, as distinct from the subsoil”. Soil is formed when rock disintegrates over time and is infused with animal excretion and additions to biomass through plant litter. Only a few centimetres of topsoil is formed over a century and factors such as erosion and disturbance through anthropogenic impacts further impede the formation and re-formation of topsoil (De Groot *et al.*, 2002). According to Ghose (2001), topsoil is critical and should be treated with the utmost care to prevent contamination or disturbance during mining. Topsoil contains the primary nutrients that vegetation requires for germination and growth. The chemical, biological and physical nature of topsoil is therefore changed when stripped and stored, leading to a “shelf-life” for the successful re-use thereof (Kundu & Ghose, 1994). Stripping and stockpiling of topsoil should be undertaken with thorough planning to ensure that negative factors, such as compaction or chemical pollution are minimised. The correct quantities and layers (500 mm) of topsoil should be removed from the selected area before mining commences. The topsoil should also be stored separately and not for long periods of time as the texture, structure and chemical composition may change over the long-term (Ghose, 1994). Miller and Jastrow (1992) also mention the importance of soil biota within topsoil layers, which positively affect vegetation establishment and may be important in soil formation, structure and nutrient cycling.

1.3.1.2 Spoil shaping

Mined overburden materials are replaced and shaped according to TSF civil engineering specifications, project schedules, budget availability and type of mining activity. The spoil is placed to form the desired or approved TSF topography (Mohr-Swart & Tanner, 2007). Key considerations for spoil shaping are erosion minimisation, free-draining capabilities and available land for spoil placement. These factors influence the suitability of rehabilitation efforts because of surface area minimisation, the bulking factor of different minerals (which can vary from 15 to 25%) and changes to mining plans (Mohr-Swart & Tanner, 2007). From a rehabilitation

perspective, spoil shaping should consider optimal slope lengths and angles, compaction, surface water runoff capabilities and the requirements of the mine-specific environmental management plan (EMP).

1.3.1.3 Soil replacement

The most important factor regarding soil replacement is the pre-mining stripping of topsoil and subsoil layers (Mohr-Swart & Tanner, 2007). Soil horizons should be replaced in the following order: usable subsoils on the reshaped spoil material, underlying topsoil material (100–400 mm) and, lastly, topsoil material containing micro-organisms and available seedbank (100 m maximum). Most importantly, compaction and loss of topsoil horizons should be avoided when attempted with soils that have high moisture content (Mohr-Swart & Tanner, 2007).

1.3.1.4 Soil amelioration

Soil amelioration should be considered a two-pronged attempt – firstly, due to the soil replacement during shaping compaction occurs. Few solutions exist for compaction other than deep ripping of soil to allow for chemical amelioration and root establishment of vegetation. When soils are ripped (to underlying overburden level) a few negative consequences are encountered such as the loss of the organic-rich layer and the mixture of topsoil and subsoil. Plant-available nutrients in the topsoil layers are diluted through nutrient poor subsoil's. This might seem easily solved through applications of magnesium, calcium and phosphorus to improve immobile chemical requirements, but mobile chemical requirements such as nitrogen and potassium are more difficult to remedy (Van Deventer, 2002). Secondly, chemical amelioration then becomes necessary by establishing plant nutrient requirements and addition of fertilisers to meet these demands, which normally exceed agricultural requirements (Mohr-Swart & Tanner, 2007).

1.4 The impact of certain minerals on the environment

The earth's crust consists of elements that form various substances we know by collective nouns such as soil, rock and water. These elements are illustrated and explained by the periodic table (Spitz & Trudinger, 2009). Of the 109 known

elements, 86 are metals and 25 non-metals. With this in mind, the fact that over 80% of the earth's crust is made up of non-metals, reveals the nature of the mining industry and the economic value of mineable ores in the world.

The most common harmful elements to the environment include arsenic, cadmium, chromium, lead and mercury (Mendez & Maier, 2008). Although these metals are considered harmful, and in some cases life-threatening, it is only at certain concentrations and when exposed to reacting elements that the impacts are exacerbated. This is mostly associated with certain mining operations. "Heavy metals" is a term frequently used to describe environmentally harmful elements, but negative impacts are only caused when these heavy metals are used in isolation (Spitz & Trudinger, 2009). Examples of heavy metals include arsenic, cadmium, chromium, lead, manganese and mercury (common associates of base metal sulphide deposits). The United Nations Environment Programme (UNEP) define heavy metals as metals that have a density of 5 g/cm^3 (38 elements) or those elements with an atomic number of more than 20 (Eby, 2004; UNEP, 1994). A simpler definition might be that heavy metals are those that are not essential to a biological system and are toxic in relatively low concentrations, especially for the establishment and growth of vegetation (Eby, 2004).

Metals occur in different physical and chemical forms and also revert to different forms after mining and production operations. Unlike organic compounds, metals cannot be degraded chemically or bacteriologically into simpler constituents and are therefore classified as persistent. In rock, metals occur most commonly as sulphides or silicates. When sulphide minerals, for example, are exposed to atmospheric conditions or processes, they decompose and liberate some metals in a soluble form. These metals become bioavailable once they are dissolved in surface or groundwater (Spitz & Trudinger, 2009).

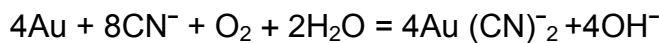
Mining and the effect of oxidised metals are most commonly found because they leach into surface and groundwater, from dust emissions and tailings solutions amongst others (Spitz & Trudinger, 2009). Leaching of these metals depends on their solubility, which is influenced by chemical parameters individually or as a combination, for example, pH, redox potential and occurrence of organic and inorganic complexing agents. Most commonly, a decrease in water pH will cause

solubility and increase leaching of most metals, a process normally found during ARD, which occurs during gold mining specifically.

1.5 The impact of gold mining on the environment

Approximately 20% of all sodium cyanide (NaCN) produced has been used by the mining industry since 1887 because of its ability to dissolve gold in water (at relatively low concentrations) by using oxygen as oxidising agent. A diluted form of approximately 0.01% and 0.05% (100 to 500 parts per million) is used in gold mining (Logsdon., 1999). A major influence of the gold mining process is the effect of cyanide on the environment. Cyanide is a compound of carbon and nitrogen and occurs naturally in some microorganisms, plants and insects (Akcil, 2002).

A common concern related to gold mining is the use of cyanide for the extraction process (Logsdon., 1999). The active ingredients in the gold mining process are cyanide ions (CN⁻), which are used in tank leaching or heap leaching processes. Gold ore is dissolved by complexation, which forms a solution and later allows for the gold to be extracted, as shown by the following formula:



Cyanide accidents have occurred over the world as shown by Hilson and Monhemius (2005) in Table 1.1.

Table 1.2: Cyanide-related mine accidents and environmental impacts as shown by Hilson and Monhemius (2005).

Table 1
Examples of recent cyanide-related mine accidents and resulting environmental impacts [6]

Company/Mine	Location and date	Impacts
Galactic Resources Ltd.'s Summitville Mine	Colorado, USA, 1992	Caused severe environmental problems along a 17-mile stretch of the Alamosa River
Pegasus Corporation's Zortman-Landusky Mine	Montana, USA, 1997	Severe contamination of groundwater; substantial wildlife deaths
Echo Bay's McCoy/Cove Gold Mine	Nevada, USA, 1989 and 1990	Eight cyanide leaks over a two-year period released almost 900 lbs of cyanide into the environment
Kumtor Mine	Kyrgyzstan, 1998	Almost 2 t of sodium cyanide was accidentally released into surface waters
Cambior Mining Company's Omai Mine	Guyana, 1995	Released more than 860 million gallons of cyanide-laden tailings into a major river

Today it is manufactured chemically and is available as sodium cyanide for mineral processing (Kettel, 1982). Cyanide used in mining is closely linked to occupational health concerns and environmental risks. Even at these low concentrations and even if cyanide neither is carcinogenic or mutagenic nor bio-accumulates, the environmental risks associated with this compound is threefold:

- Cyanide-containing ponds and ditches present extreme risks to wildlife;
- Spills can reach ground- or surface water and have widespread short- to long-term negative effects; and
- Cyanide in active heaps and mining wastes (spent ore, tailings impoundments) could reach the environment and have widespread negative impacts on biodiversity and human health.

Furthermore, cyanide increases the potential for some metals to become soluble and increases the toxic effect due to transportation. Typically encountered concentrations of residual cyanide in gold mine tailings are approximately (in the range of) 80–400 mg/L, of which 50% is weak acid dissociable (WAD) cyanide, which is readily released from cyanide-containing complexes when the pH of the environment is lowered.

The presence of cyanide in gold tailings TSFs requires treatment in applicable cases to allow safe disposal (Spitz & Trudinger, 2009). The most common ways to reduce toxic levels and ensure safe disposal include:

- Volatilisation (natural degradation), which is enhanced by exposure to sunlight;
- Introduction of non-cyanide-bearing water, i.e. dilution;
- Oxidation through the use of several oxidants, including hydrogen peroxide (H_2O_2), chlorine – in the form of calcium or sodium hypochlorite ($NaClO$) – or sulphur dioxide (SO_2); and
- Through recovery and re-use by lowering the pH to form hydrocyanic acid (HCN), which is volatilised and re-dissolved into the applicable leach solution.

The impact that cyanide would have on the trials undertaken during this study and the associated vegetation establishment is apparent when considering the above. This also shows the challenge for long-term sustainable TSF rehabilitation.

ARD has the potential to become problematic in most mining activities where the ores mined are surrounded by rock containing sulphide minerals (pyrite (FeS_2), pyrrhotite). ARD is commonly associated with gold mining but is also encountered in copper, silver, lead, zinc, nickel and coal mining operations. ARD is a natural process that only requires oxygen, moisture and heat for the reaction to take place, after which the process/reaction continues to develop. Pyrite is naturally found in organic clays, silts and peats that deposit in reducing environments (Spitz & Trudinger, 2009).

Oxidation of pyrite commonly occurs slowly with a decline in pH. When the pH reaches approximately 3.6, oxidation speeds up. During this process, sulphuric acid is formed, which is highly reactive to adjacent minerals, leading to the formation of sulphate salts. In the presence of calcite, gypsum may also form as part of the reaction. Each metal in solution produces its own metal acidity to the ARD solution and precipitates at different pH levels (Kalin *et al.*, 2005).

ARD occurs most commonly during the following stages of a mining operation:

- Runoff from excavation (surface);
- Mine access – underground excavation seepage;
- Open pit mines – runoff from exposures in the retaining structure;
- Stockpiled ore runoff;
- Coal reject and/or waste rock storage; and
- Overflow from TSFs.

The effect of ARD can therefore be crucial and pose major risks to any mining operation with associated minerals and mining processes. Although new procedures for identifying, quantifying and controlling ARD and its associated impacts are being developed, the ecological, operational and societal effects can be far-reaching and serve as a critical factor when determining the lifetime of a mine and the economic survival over the long-term. ARD is specifically detrimental to vegetation establishment by the high concentrations of available H^+ ions in acidic soils. Along with the phytotoxicity of dissolved Fe^{2+} ions, the germination and survival of vegetation on acidic mine TSFs decrease significantly (Bell *et al.*, 2001).

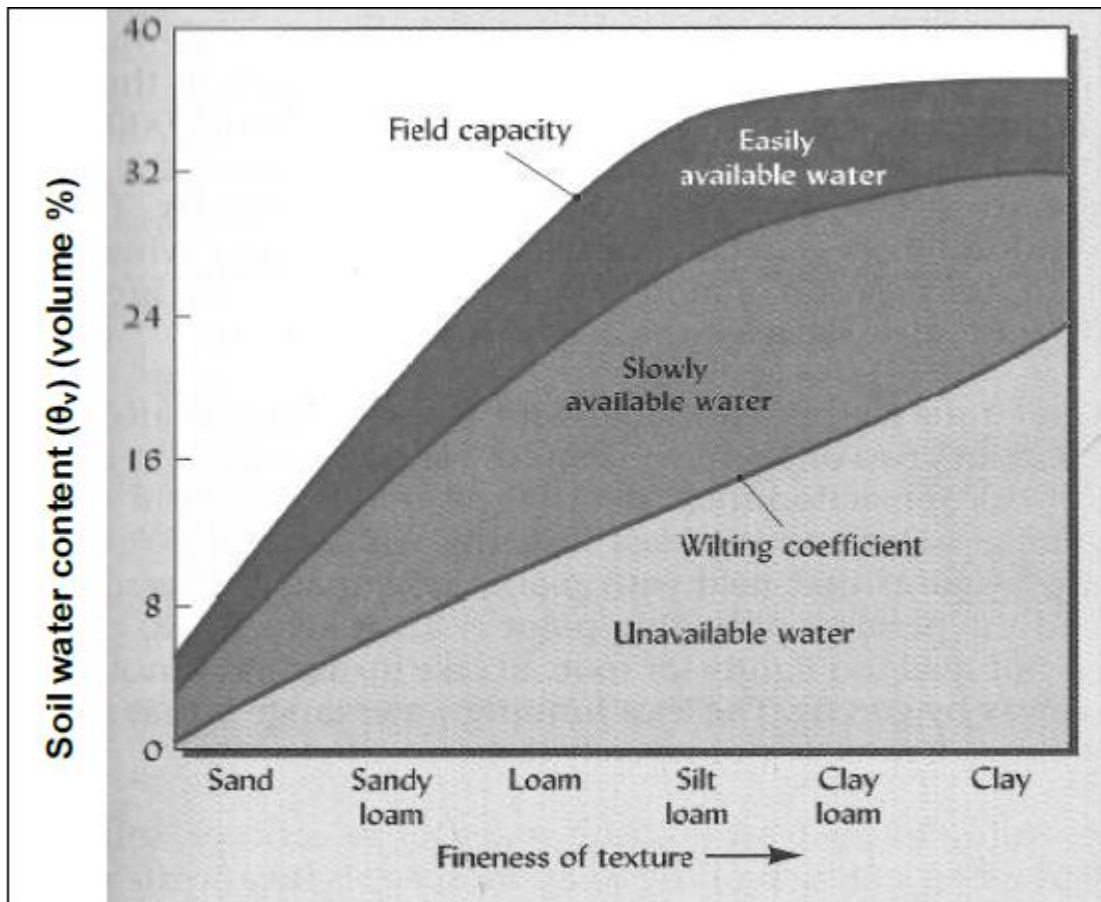


Figure 1.1: Indication of soil water (volume) availability vs. soil texture fineness (Brady & Weil, 2008).

As a result of the combination of factors discussed above, the biological and ecological function on a TSF is also impacted, thereby reducing the capacity for rehabilitation and stabilisation by vegetation. As seen in Figure 1.1, the soil texture further causes vegetation stress due to unavailability of water in gold and platinum TSFs (Brady & Weil, 2008). Also, because of the non-existent soil structure often observed on TSFs, only severely stressed heterotrophic microbial communities can be sustained (Mendez *et al.*, 2007). This leads to low carbon utilisation when compared to non-contaminated soils. On platinum TSFs specifically, the establishment of vegetation is further hampered by certain physicochemical factors impacting the plant growth, such as high soil and surface temperatures, low precipitation and high wind speeds. This is exaggerated by high salt concentrated soils and low water infiltration (Munshower, 1994).

1.6 The impact of platinum mining on the environment

The most critical phase of a platinum TSF is during its operational lifetime because of stability and operational requirements. Effective monitoring and measurement are therefore critical to the successful and safe establishment and survival of vegetation on these TSFs (Boshoff & Hamman, 2011). Platinum TSFs are generally constructed with a one-in-three slope (for every unit of measurement horizontally, three equivalent units move vertically, for example, 1 m horizontally equals 3 m vertically), which is considered challenging, especially with regard to the establishment of vegetation, considered critical in terms of mine closure (Boshoff & Hamman, 2011). In some cases, waste rock is also used to attempt additional stabilisation of slopes, generally constructed with “step-ins” that allow access and erosion control because of runoff buffers (Boshoff & Hamman, 2011). Platinum TSFs are generally considered less problematic in terms of vegetation establishment when compared to those of gold mines due to the removal of acid-bearing sulphides during the floatation procedure. Therefore, a higher soil pH on platinum TSFs than on gold TSFs can generally be expected (Muller, 2014). Proper rehabilitation planning, monitoring and maintenance are still required, with correct plant species and soil ameliorants considered to achieve the best possible success.

Platinum TSFs generally produce large quantities of airborne dust, especially during the dry winter months in the areas where platinum mines are situated in South Africa. This enforces the need for successful and timely rehabilitation because of the impact of dust particles on vegetation establishment as well as the inherent health risk and nuisance factor associated and experienced by neighbouring communities. Boshoff and Hamman (2011) identified three different particle ranges on platinum TSFs in the Bushveld Igneous Complex, namely respirable ($<7\ \mu\text{m}$), thoracic ($7\text{--}10\ \mu\text{m}$) and inhalable ($>10\ \mu\text{m}$) with average occurrence percentages of 9.72, 2.95 and 87.28%, respectively. Although this was the common finding, Loubser (2009) indicated that the risk of toxic consequence remains extremely low. The most problematic factor associated is therefore the nuisance of windblown dust.

Loubser (2009) further indicated that the mineralogy of a platinum TSF has implications for ground- and surface water, namely that the tailings material generally remain geochemically inert due to the removal of sulphides. Sufficient residual

sulphides nonetheless remain, which, upon oxidation and in-situ neutralisation, release sulphates dictated by gypsum solubility. This seepage may contain higher-than-proposed domestic use levels of sulphates, calcium and magnesium. Salts and ammonia-nitrate, which are the residues from blasting operations, can also remain in the tailings material and are often found in elevated concentrations at especially the toe of the TSF.

1.7 Industry-related rehabilitation technology for gold and platinum TSFs

Although mine TSF rehabilitation has developed extensively and continues to evolve, new technology continuously attempts to produce new and innovative ways to deal with the by-product of the economic boost that follows the mining operations. Rehabilitation efforts at gold and platinum TSFs depend on the availability of funds, project management initiative, TSF placement and construction, availability and influence of natural elements (water, temperature, wind velocity), availability of soil amelioration agents (fertiliser, lime, compost, mulch) and the scientific knowledge to carry out the rehabilitation process correctly (Spitz & Trudinger, 2009). In the rehabilitation methods that are planned, two conventional options are commonly considered:

1. In-situ treatments include the use of methods of rehabilitation on site, such as vapour extraction and soil flushing.
2. Ex-situ treatments include the use of methods to excavate and treat TSF material elsewhere, such as solvent extraction (leaching) and soil washing.

The conventional treatment options that are commonly applied at gold and platinum TSFs with proven success, include:

- Chemical treatments (in-situ and ex-situ). The purposes of chemical treatments are to destabilise, modify or destroy the harmful organic or inorganic contaminants encountered. Chemical treatments seldom occur in isolation but are employed as a pre- or post-process amelioration option. When applied as a pre-process option, common chemical amelioration includes the addition of lime to raise pH levels to a suitable standard for

vegetation to be able to establish and survive as part of the rehabilitation process (Spitz & Trudinger, 2009).

- Stabilisation and solidification consists of treatments that contain/reduce TSF material into a less soluble, less environmentally available (mobile) state. This includes treatments in terms of chemical or physical solidification. Solidification also includes measures such as micro- and macro-encapsulation to address particle size distribution and variability in different TSF waste. Solidification serves as an interim measure in many cases where the solidifying agent breaks down over time, therefore requiring additional control such as vegetation establishment or re-application of solidifying agents.

Further consideration for rehabilitation must include the consistency of platinum TSF material and the impact thereof on rehabilitation methods. Platinum tailings consist of 75% sand and 20%, while the remaining 5% is represented by the clay fraction, which could also influence the germination, establishment and growth of vegetation during the rehabilitation process (Maboeta & Van Rensburg, 2003).

1.7.1 The critical role of plant nutrient availability

The role of vegetation is of critical importance for the rehabilitation process and is often influenced by the chemical and physical soil properties. Approximately 14 elements critical to the survival of plant species are encountered in the soil and are supplemented by inorganic fertilisers where these elements are lacking. To become available to the plant, elements have to occur in a soluble form. These elements are classified in three distinct groups, namely:

1. Primary elements – nitrogen, phosphorus and potassium;
2. Secondary elements – calcium, magnesium and sulphur;
3. Microelements – boron, chlorine, copper, iron, manganese, molybdenum, nickel and zinc.

In the process of gold and platinum mine rehabilitation, the TSF material is mostly devoid of organic material and it is necessary for soil microbe activity to enable the

availability of the micro- and macro-elements required for plant germination, growth and survival (Spitz & Trudinger, 2009).

From Figure 1.2, it is evident that the pH value directly influences the availability of micro- and macro-elements and also shows the impact of availability of aluminium at low pH, which influences vegetation establishment negatively when toxic.

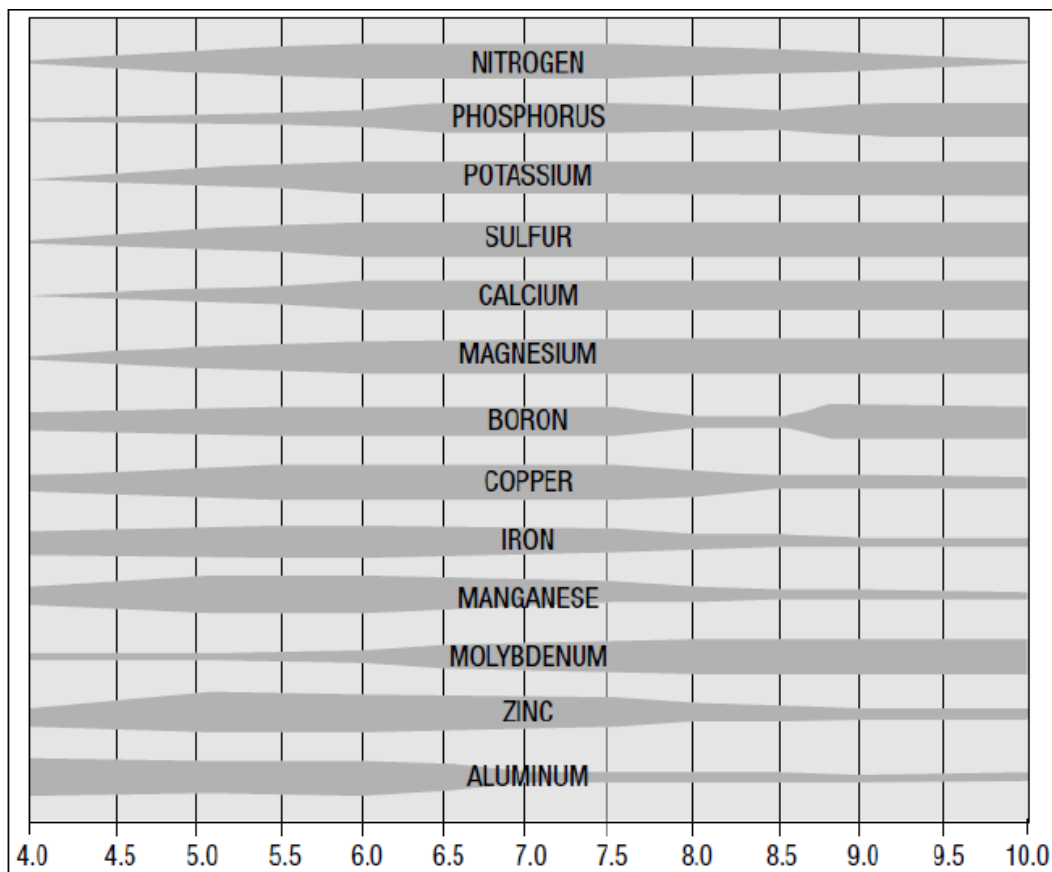


Figure 1.2: Plant-available nutrients range in comparison to different pH levels (Beegle, 2001).

1.7.2 Functions of plant nutrients

Nitrogen is critical for key processes such as photosynthesis, growth and reproduction and becomes available in a nitrate (NO_3^-) form, after which it is reduced to NH_2 . It manifests in plant amino acids, protein, adenosine triphosphate (ATP), adenosine diphosphate (ADP), deoxyribonucleic acid (DNA) and phospholipids. From Table 1.2 (and the soil sample results described in Chapter 4), it is clear that this critical element would not have been available to the plants used in the trials for this study before amelioration (FSSA, 2007).

Phosphorus is mainly available in a soluble orthophosphate (H_2PO_4^-) form and also has an important function in ATP, ADP and DNA. It is important for overall growth and especially cell division, root growth and flowering. However, it is only available in small quantities at a pH of <6 (FSSA, 2007).

Potassium is required in large quantities by plants. It occurs in the cell sap and transports nitrogen, is used for the translocation of starch and benefits photosynthesis (FSSA, 2007).

Magnesium forms the core of the chlorophyll molecule, without which photosynthesis would not be able to take place. Magnesium shortages are commonly encountered in acidic sandy soils, similar to that of gold mine TSFs, although high magnesium levels in relation to calcium can further cause soil compaction (FSSA, 2007).

Sulphur is commonly encountered in a sulphate form (SO_4^{2-}). After reduction, it forms part of amino acids such as methionine, thiamine and biotin, which are the building blocks of proteins and therefore impacts plant growth (FSSA, 2007).

Calcium is encountered in the middle lamella of the cell wall in a calcium pectate form and is immobile in the plant. It enables the formation of protein and is crucial for cell growth. (FSSA, 2007).

Zinc plays a role in the activation of enzymes, regulates pH cell liquids and is also part of the formation of chlorophyll and growth hormones. Zinc shortages are usually encountered at high pH levels, especially in platinum TSFs. This influences the growth, structure and development of plant cells (FSSA, 2007).

Manganese plays an important role in photosynthesis and oxidation reduction reactions in the plant (for example the reduction of nitrates). Furthermore, it enables the metabolism of iron as well as enzyme activity (FSSA, 2007).

Copper is found in the seed and growing parts of the plant and is part of the respiration process as well as being the catalyst of various oxidation processes within the plant (FSSA, 2007).

Iron plays an important role in the oxidation-reduction processes of the plant and specifically the formation of chlorophyll. It is also found in enzymes and certain proteins (FSSA, 2007).

Boron is absorbed in the boric acid format ($B(OH)_3$) and plays a structural part in pectin and lignin synthesis. It also improves cell differentiation and the transport of carbohydrates and phosphate ions over membranes. However, high levels of boron is damaging to the plant (FSSA, 2007).

Molybdenum is only required in very small amounts by the plant. It plays an important role in the reduction of nitrates during photosynthesis. Shortages in South Africa usually occur in acidic, leached soils. Molybdenum also plays a role in the forming of nodules on leguminous plant roots and in the functioning of nitrogen-fixing bacteria (FSSA, 2007).

1.8 Rehabilitation

1.8.1 Re-vegetation and biodiversity re-establishment

Post-closure land use remains the most important factor for plant species selection and rehabilitation techniques employed. The specification of biodiversity requirements largely influences the required techniques and research applied to implementation and monitoring of the rehabilitated area (van Deventer, 2008).

Vegetation cover by re-grassing is considered one of the preferred rehabilitation techniques in South Africa. However, because of the availability of materials and legislation requirements, it is often not considered the most effective or successful method (Rossouw *et al.* 2009). Vegetation cover serves as a secondary surface stabilisation mechanism, alters water balance and improves aesthetics (van Deventer, 2008). The type and method of re-vegetation for rehabilitation depends on a number of factors. These mainly include various aspects of the type of growth medium, such as particle size distribution, water retention, water holding capacity, infiltration rate, runoff rate and geochemical toxicity (acidification and salination).

Alien species are often used for rehabilitation of TSFs because of their fast growth and adaptability. Alien invasive species have, however, been shown to out-compete indigenous species and it is difficult to control them. The use of alien species also does not comply with national environmental legislation as per the National Environmental Management Biodiversity Act no 10 of 2004. Therefore, locally adapted species should be considered a priority, as should the amelioration of soil

required in terms of nutrient availability for plant growth. Species such as legumes are commonly used to improve nitrogen availability in the soil.

Seed mixes are a preferred method whereby annual and perennial species are sown together to allow for swift establishment and long-term survival, contributing positively to the ecosystem over time. One of the main objectives of vegetation establishment is to mitigate the effects of wind and soil erosion, which can create water and dust pollution. To enable species to grow and establish, many rehabilitation efforts attempt to minimise wind speed through shade netting tunnels, which also improve vegetation survival. Established vegetation with good root systems also decrease soil erosion, especially when re-vegetation is done on steep TSF slopes.

As mentioned above, correct soil chemistry is critical to vegetation re-establishment with the required amelioration. Other factors to consider include the climatic conditions in the area (especially rainfall and temperature), the time window available for seed germination and plant establishment, as well as the monitoring and maintenance requirements associated therewith (Van Deventer, 2008).

The availability of appropriate seed, used in re-vegetation activities, in high quantities is also a crucial factor. Reputable seed production companies and seed of high quality should be considered to reduce chances of germination and establishment failure (Torok *et al.* 2011). The type of seed application and correct seeding ratios depend on the land-use requirements and are often combined with selected species and seed type to deliver good results over time. Re-seeding activities also require good management and maintenance over time.

Different methods of re-seeding exist and are adapted according to site-specific requirements and practical implications. This includes broad-cast and row re-seeding activities, mostly by hand, depending on the site-specific requirements. The steepness and accessibility of TSFs should be considered. This is especially true when re-seeding is carried out by a tractor-mounted seed spreader, hydroseeding and in mulch layers (seeding using slurry containing mulch and/or seed). Vegetation maintenance and erosion control is also crucial to the survival of the “newly formed” ecosystem as nutrient requirements and levels may fluctuate over time (Van Deventer, 2008). Soil characteristics play a critical role as indicated in Figure 1.3

where the different soil types/growth mediums and their individual characteristics indicate the importance of correct rehabilitation techniques to be applied in a site specific way.

Table 1.3: Generally anticipated soil characteristics that could be problematic for vegetation covers on different tailings types (Van Deventer, 2008).

	Compaction or crusting	Moisture retention	Infiltration	Sodicity*	Salinity	
Andalusite	✓		✓	✓	✓	
Antimony	✓				✓	
Chrome	✓	✓			✓	
Copper		✓	✓	✓	✓	
Foskorite		✓			✓	
Gold	✓		✓		✓	
Kimberlite		✓	✓	✓	✓	
Platinum		✓			✓	
Silica		✓	✓			
	Acidity (ARD**)	Alkalinity	Heavy metals	Dispersion	Dust	Low water retention
Andalusite		✓				
Antimony		✓	✓	✓		
Chrome		✓			✓	✓
Copper		✓				
Foskorite	✓	✓		✓	✓	✓
Gold		✓	✓	✓		
Kimberlite	✓		✓	✓	✓	✓
Platinum	✓			✓	✓	✓
Silica	✓					

*Sodicity: amount of sodium held in soil

**ARD: acid rock drainage

1.8.2 Biodiversity offsets

Offsets, also known as set asides, compensatory habitats and mitigation banks, are commonly used and legislated across the world (Gibbons & Lindenmayer, 2007).

They were instituted to compensate for total biodiversity loss due to anthropogenic impacts and are used in addition to other environmental management strategies. The purpose of biodiversity offsets is to replace an impacted area with a similar area (economically and biodiversity-related), which is managed and supplied as the “offset” for the impaired/damaged area. Although many industries and specialists support biodiversity offsets, one drawback is that natural areas are impacted and are not rehabilitated (loss of natural area) and that quantification and replication of natural areas are close to impossible (Burgin, 2008).

1.9 Conventional methods

Conventional rehabilitation methods, such as covering polluted soil with fertile soil for re-vegetation, rock cladding¹, encapsulation by using concrete or similar material (usually not cost effective) and ex-situ soil remediation, are commonly considered as expensive techniques (Franks *et al.* 2011).

Rehabilitation is often carried out by so-called “physical stabilisation”, which entails the use of an innocuous material such as rock or topsoil to cover or clad mine waste TSFs. The consideration of these methods have to include the financial costs, availability of material and suitability of the TSFs for vegetation establishment (Johnson & Bradshaw, 1977). Rock cladding involves un-graded and un-screened material, because of the high costs of screening for appropriate size-limits, and differs from rock armouring. The latter involves stony soil (a mixture of topsoil and rock) that acts as a cover material and inhibits crust formation. These covers are usually re-vegetated, but not with the main purpose of stabilisation (Johnson & Bradshaw, 1977). Costs for the above accumulate because of the need for heavy machinery, transport, labour and sourcing of suitable materials (Johnson & Bradshaw, 1977).

Soil manipulation during topsoil removal and replacement plays a large role in this process, as chemical fertilisers and minerals such as lime are used – sometimes in great quantities – to change soil properties to such an extent as to allow successful establishment and growth of vegetation (Kalin *et al.* 2006). These methods incur

¹Rock cladding: placement of rock layers over the surface of a TSF, essentially covering it to form a wind- and erosion-efficient solution to TSF stability.

costs and rely on continual management of rehabilitation sites over years because of the inhospitable nature of TSFs and associated climatic conditions. Although these are preferred methods of rehabilitation, many factors may vary between sites and thus there is a need for scientific knowledge or experience in agricultural or chemical requirements of soils for vegetation establishment.

Slope also plays an important role in rehabilitation planning and it influences the choice of plant species for stabilisation and accessibility for mechanical implements to create and re-vegetate the TSF. These methods also require continual post-rehabilitation monitoring and management to assess the success or failure of the applied methodology (Mohr-Swart & Tanner, 2007). Additionally, soil amelioration can be included in the method, depending on the chemical composition and texture of the TSF material. A lignin sulfonate or a resinous adhesive is also commonly used to stabilise the steep slopes of TSFs, which helps to provide a crust that controls wind and water erosion. Although this serves as a relatively quick solution, it is unfortunately not permanent and has to be monitored frequently (Tordoff *et al.*, 2000).

1.10 Phytoremediation

Phytoremediation is a plant-based technology that uses specific groups of plants – known as metalophytes – to extract metals from soils through their ability to survive conditions commonly known to inhibit growth. The aim is to volatilise, stabilise, neutralise, degrade or extract the pollutants in soil through the use of either phytostabilisation, thereby reducing the bio availability of pollutants to acceptable limits for specific plant species, or phytoextraction, which removes the toxic pollutants completely (Huang *et al.*, 1997).

The ultimate goal of any rehabilitation plan should be to return the area to a natural state that can contribute to ecosystem function and, if possible, add similar value as the previous land use. However, this would be possible for opencast mines, but not tailings dams (Lubke & Avis, 1999).

For this dissertation, the term “rehabilitation” will be used as process where disturbed land is returned to a stable, productive and self-sustaining condition, taking future land use into account. Furthermore, disturbed land is used as reference to the “new

ecosystems” created by mining processes as these areas (TSFs) are being rehabilitated rather than the physically disturbed land of the mine itself.

1.11 Advanced methods to increase seed survival

Research has been conducted regarding the possibility of creating improved/“super” seed that improve yields, survivability, germination, size, growth and production timeframes. Some research, for example, tested the effect of smoke and heat on emergence of seedlings. In Australia, seed were subjected to cool smoke and heat and it was found that smoke alone triggered emergence of up to 4.3 times higher in grasses especially (Read *et al.*, 2001).

Research has been done on seed coating, which is of great importance to this dissertation (Brady, 1989). Seed coating commenced as early as the 1930s, although at that time the main purpose of coating was to establish uniform seed size. Further studies were conducted and products developed that attempted to enhance seed germination and survival through inclusion of specific ingredients related to the stimulation of growth (Brady, 1989). These enhancements included fertilisers, pesticides, fungicides, herbicides, micro- and macronutrients, surfactants, growth regulators, polymers and germination stimulators.

The purpose of seed coating is to influence the microenvironment of the individual seed during seed-soil interaction (Barke *et al.* 1981). This leads to a reduction in the use of fertilisers as broad spectrum treatments and an increase precision farming and/or rehabilitation techniques. Although there have been numerous studies regarding seed coating, or pelleting as it is sometimes known, many studies have not been able to correlate findings due to the unavailability of seed coating formulas (Taylor & Harman 1990). Each manufacturer attempts to establish confidence in their product and uses different materials to evolve their seed coating to a level which is undisputable in the industry. Naturally there is some cause for secrecy in an industry where competition is so closely monitored (Brady, 1989).

Seed coating at AGT Foods Africa (Pty) Ltd ²(henceforth AGT Foods Africa) has developed to enable the company to become one of the leaders of this technology in Africa. Their brand of seed, AgriCOTE, is coated using rotary coating equipment that is computer-assisted and automated to ensure uniform coatings and pliability in terms of coating formulas. AGT Foods Africa also strives to use scientific data from university research to promote, sustain and improve their product.

1.11.1 Re-seeding of disturbed environments

According to Van den Bergh and Kellner (2010), the rehabilitation of degraded ecosystems requires either active or passive rehabilitation activities. Passive rehabilitation commonly refers to the alleviation of the stress factor causing the ecosystems to degrade, such as the implementation of better grazing management strategies in response to overgrazing. Active rehabilitation, on the other hand, focusses on the use of agricultural implements, such as rippers and ploughs to disturb the degraded soil surfaces for improved moisture infiltration and/or the application of organic material, which are often followed up by re-seeding to enrich the soil seedbank that is normally depleted in degraded soils.

This study focussed on active rehabilitation methods and included the re-seeding of grass species on mine TSFs to minimise erosion by wind and water, decrease high temperatures and increase water infiltration for better vegetation establishment. Re-seeding entailed the addition of viable seed that was obtained from a seed company who encapsulates (coats) for better germination and establishment. According to Anderson *et al.* (1957), re-seeding should occur in a prepared seedbed while considering the factors mentioned above that will impact on vegetation establishment.

Degraded areas on gold and platinum mine TSFs also require extensive chemical and biological amelioration measures, as the soil structure and composition is commonly devoid of life-sustaining plant nutrients and typically contains toxic levels of detrimental elements, have low water retention capacity, high soil temperatures

² AGT Foods Africa (Pty) Ltd
8 Jacons street, Chamdo.
Krugersdorp

and little to no biological and organic material. Different grass species (annuals and perennials) adapted to the site-specific conditions are often mixed with nitrogen-fixing legume species, such as alfalfa (*Medicago sativa*), to enrich the soil for long-term plant establishment. These factors influence the ability and success of reseeded mine TSFs.

Although local species adapted to the specific habitat encountered on TSFs are first choice options for rehabilitation, the reality is that seed of many local plant species are not commercially available, especially in the large quantities often needed for rehabilitation.

As mentioned by Gunn (1973), the rehabilitation of mine TSFs has been attempted since the late 1800s to reduce dust pollution. These attempts were at that time largely unsuccessful and short-lived. The intrinsic value of current research and scientific solutions should therefore not be underestimated.

Furthermore, the success of rehabilitation efforts through re-seeding to improve the vegetation cover is often debated as it requires long-term management and maintenance (Cairns, 1995). Scientific inputs regarding rehabilitation should also be incorporated and be part of the end-use of any rehabilitation process. This is especially true if different species compositions are used, where basal cover, biomass production and establishment of the plants differ. Moreover, the sequence of climatic and biological cycles required to develop and sustain a natural ecosystem can never be completely re-enacted or repeated. Common indicators to monitor and establish successful ecological rehabilitation over time are mentioned in Table 1.4 (Tongway & Murphy, 1999). Many of these factors are used as scientific proof of re-vegetation and successful vegetation establishment, which depend on the site-specific EMP for TSF rehabilitation.

The fact remains, mine TSFs create new and unresponsive soil mediums that remain ecologically challenging, therefore limit the supporting capability of long-term ecological sustainability.

Table 1.4: Ecological monitoring criteria applicable to mine tailing storage facility (TSF) rehabilitation.

Indicator	Monitoring criteria
1. Geotechnical stability of TSF	Structural importance; key to rehabilitation efforts
2. Erosion factor	Current erosion and of degree of possible erosion in future, ability of surface to handle mechanical disturbances.
3. Available soil cover	Use of TSF material as soil cover or possible topsoil availability.
4. Water infiltration	Possibility of rust formation, infiltration rate and evaporation percentage (water-holding capacity).
5. Available soil nutrient capacity	Status of soil nutrient availability and nutrient cycling requirements to be established
6. Species chosen in rehabilitation seed mix	Assess monitoring data of established vegetation against land-use requirements for TSF
7. Land use/ecological function	Long-term monitoring of ecological function and stability
8. Environmental/social impact	Evaluate the impacts on the surrounding environment and community as well as the improvements made

1.12 Seed coating

One successful and innovative way of establishing vegetation, raising yield quantities and improving overall seed germination and plant establishment is seed coating (also known as seed enhancement) and it has evolved and developed new ways to approach vegetation establishment. South Africa established its first seed qualification and trade bodies as early as the 1940s, but only started consolidating these institutions into the Association of National Seed Organisations (SANSO) by the 1980s (Zingel *et al.*, 2007). SANSO developed into what is known as the South African National Seed Organisation (SANSOR) today. Under the Plant Improvement Act 53 of 1976, seed certification, in combination with the seed industry as a whole, is regulated to ensure the availability of quality seed through its governing body, SANSOR. The certification and import and export of seed types are controlled in this manner, which ensures that applicable standards and additional South African environmental legislation requirements are met (Zingel *et al.*, 2007).



Figure 1.3: Coated seed mix used in study field trial (Photo: H Taute, 2015).

Seed coating can be sub-divided into the following categories (Figure 1.4):

1. **Seed priming**, which consists of a physiological enhancement method used for certain seed to allow hydration and controlled imbibition through activation of the pre-germination metabolism (Kaufman, 1991). Priming has to be carefully controlled to stop radicle emergence and germination (Zingel *et al.*, 2007). Microorganisms and hormones that benefit the plant can be added via the priming solution. Priming allows synchronised and swift germination of seedlings that germinate uniformly in wider temperature ranges and produce higher yields.
2. **Pelleting** is the most common method for seed enhancement and involves the alteration of individual seed forms (flat or irregularly shaped seed become rounded, light seed become heavier), specifically developed to improve plantability and performance (Kaufman, 1991). Pelleting allows uniform seed to be planted with precision. Most pelleting is done by a rotating drum and consist of a filler (clay, graphite), a binding agent to ensure the filler's adhesiveness to individual seed and materials such as micronutrients,

fungicides and herbicides (Deaker *et al.*, 2006). The risk of seed pelleting is the reduction of available oxygen in mediums with high moisture content (Zingel *et al.*, 2007). Seed coating by pelleting is an economical way to improve seed performance without altering the individual seed form/shape.

A further benefit of seed coating that the coating is applied directly to the individual seed, thereby (in theory) decreasing the amount of additional chemical enhancement required after sowing/planting. Coatings are applied in a liquid form and alter seed weight by 1–10%. The coating normally consists of natural or synthetic polymers that stick to individual seed, enabling accuracy of coating formulas. Seed coating can be modified by species-specific requirements, allowing imbibition and germination to be modified to suit the purpose of the specific species or its use (Zingel *et al.*, 2007).

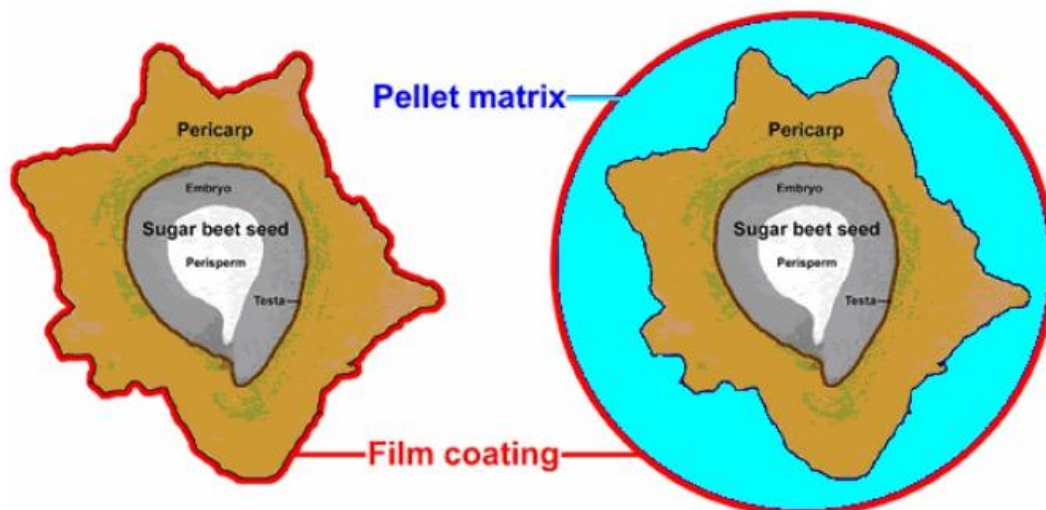


Figure 1.4: Seed coating vs. pelleting, the two categories of seed coating (Zingel *et al.*, 2007).

1.13. Policy and legislation – mining operation and maintenance.

A direct part of the approach to sustainable land use is existing policy and legislation. South Africa has continued to improve its environmental legislation and has, through trial and error, reached a point where the implementation rather than existence of legislation is the main driver of non-sustainable land uses, leaving South Africa with a considerable social, economic and environmental challenges (Swart, 2003). There are several acts that enforce legislative compliance with regards to environmental,

and specifically mining spoil, rehabilitation in South Africa. A global perspective is the origin or basis for legislation formulation and development – this is called the “precautionary principle”. This principle states that any human activity will create or have an impact on the environment, which must be considered adverse/negative until proven otherwise (Loyd, 2010). Amendments thereof at some stage have attempted to close the gap between industry and attainable environmental solutions where approval has been granted for mining. To successfully approach the subject of rehabilitation, it is critical to understand the common lifecycle of a mine as shown in Figure 1.5.

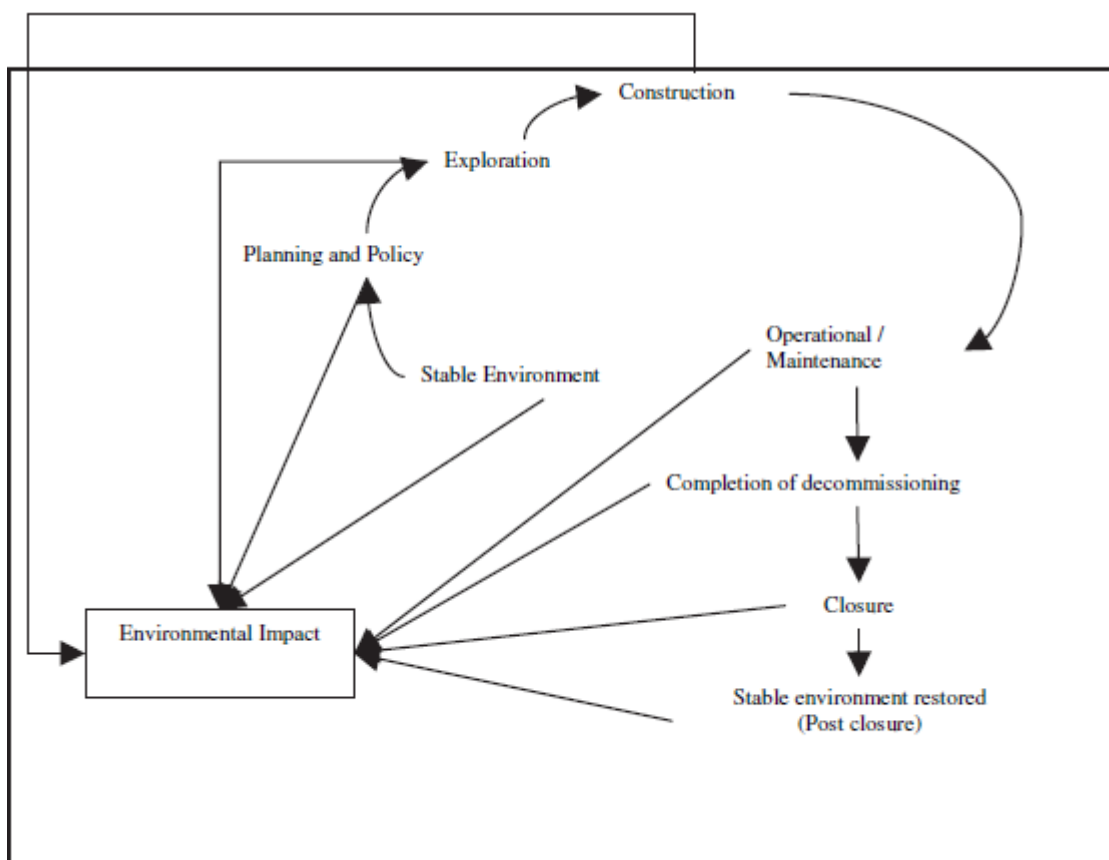


Figure 1.5: Mining and decommissioning phases (Fourie & Brent, 2005)

A typical mining operation creates environmental impacts and through correct legislation (policy) these impacts have to be controlled and managed through planning to create a stable environment. Some of these issues occur during the stages of a mine’s lifecycle as indicated by Fourie and Brent (2005). The phases of the mining procedure specifically related to environmental impacts include mining exploration (habitat disruption, waste generation and pollution) and the final phase, which involves decommissioning and closure as well as the closure certificate that

requires many aspects of rehabilitation, often with large financial and time-related inputs (Fourie & Brent, 2005; Ayres, 1997). Each of these phases requires rehabilitation inputs as they directly impact the environment.

1.13.1 Mining exploration

Airborne, geochemical and geophysical exploration, stripping, drilling, trenching and other similar activities occur in the mining exploration stage that lead to the initial causes of pollution or impacts such as initial acid mine drainage. During this phase, environmental impacts are limited, but it is already possible to evaluate the potential impacts and required mitigation strategies (Fourie & Brent, 2005; Ayres, 1997).

1.13.2 Mining and milling

Mining and milling involves stripping of overburden, ore extraction, vegetation removal and chemical treatment of mine and surface water. This phase is the most critical for rehabilitation success, as this is where the environmental impacts are highest and where the topsoil removal process and placing of topsoil become critical to the rehabilitation outcome (Fourie & Brent, 2005; Ayres, 1997).

1.13.3. Smelting and refining

Smelting and refining cause air pollution (e.g. acid rain) and chemical impacts on the surrounding environment, including impacts on human health through pollution of water resources with heavy metals, impacts on crop production and respiratory health issues, such as asthma and lung cancer, associated with air borne pollutants. If operations are planned correctly and sufficient safety, monitoring and management procedures are in place, these impacts can be managed to allow for swifter and more successful rehabilitation (Fourie & Brent, 2005; Ayres, 1997).

1.13.4 Mine closure

With mine closure, the decommissioning of roads and infrastructure, covering and rehabilitation of tailings dumps, re-contouring of waste dumps amongst others lead to the impacts that have to be dealt with before closure is granted (Mohr-Swart & Tanner, 2007). Rehabilitation of these impacts requires time and financial input. In

many cases rehabilitation is only started at the end of a mining lifecycle. Since many mines in South Africa and the world have lifecycles of more than 50 years, the accumulated impact and cost if rehabilitation is commenced at the end of a mine's lifetime rather than during the operational stage – as proposed by most specialists in this industry – are enormous (Mohr-Swart & Tanner, 2007).

Environmental legislation is also considered in the Constitution of South Africa of 1996, which states in Section 24 that “[e]veryone has the right:

- (a) to an environment that is not harmful to their health or wellbeing; and
- (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that:
 - (i) prevents pollution and ecological degradation;
 - (ii) Promote conservation; and
 - (iii) Secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.”

The Constitution of South Africa forms the basis for the application of further legislation that controls the effective management of land, water, fauna, flora and mineral resources as well as the requirement to ensure that the environment is not degraded or damaged. Degraded and disturbed land has to be rehabilitated to ensure a safe environment for all people (South Africa, 1996).

Environmental legislation through the Conservation of Agricultural Resources Act no. 43 of 1983 (CARA) (amended in 1991, 1994 and 1996) attempted to impose stricter regulations on land use overall and brought into place aspects related to environmental legislation in South Africa. CARA was improved and replaced by NEMA, which provides a framework and principles in Chapter 1 of the act for sustainable land use and remediation. Furthermore, the act states that the environment is an interrelated system requiring all spheres of Government, as custodian of natural resources, to cooperate, consult and support each other (South Africa, 1998). NEMA also clearly states that all entities or individuals have the duty of care regarding their activities, ensuring that necessary steps are taken to safeguard the natural resources of South Africa and to implement necessary remediation where

degradation could not be avoided. NEMA sets the standard for legal intervention on behalf of the environment, although it only broadly deals with the mining industry. It also represents the interests of nearby communities that are influenced by developments and attempts to find ways to prevent or repair damage to the area and its aesthetic and health impacts (South Africa, 1998).

Policy regarding the mining sector in South Africa is easily accessible and its existence well known. With regard to the impacts of mining activities, the Mineral and Petroleum Resources Development Act no 28 of 2002 builds on the principles of NEMA with clear objectives related to mining applications, permits, activities, management and rehabilitation (South Africa, 2002). NEMA requires any mining applicant to apply, through undertaking an EIA, for the right to extract minerals. Sufficient proof is required to enable the Department of Environmental Affairs and the Department of Mineral Resources to control the methods set in place to minimise the impacts associated with the mining activity (South Africa, 1998). It also allows the Government to monitor the financial availability of a mining body for rehabilitation purposes through ongoing procedures and during closure application.

Environmental legislation in South Africa do not stand apart but are interrelated to ensure that all spheres relating to environmental impacts are managed, approved or declined and rehabilitated successfully. As part of the EIA process, a number of acts have to be considered. These include the National Water Act 36 of 1998, which controls the use and permit requirements for water usage and pollution, the National Environmental Management Biodiversity Act 10 of 2004, which controls permits for alien and invasive species control and movement as well as for the species that must be protected because of dangers of extinction whilst guiding users on the possible avenues of successful rehabilitation, the National Environmental Management Waste Act 59 of 2008, which controls the pollution of natural resources and provides permit requirements for storage and production of waste. CARA and many others acts, along with internationally recognised management systems such as ISO 14001 and 18001, add to the many environmental protection specifications in South Africa.

Because of the nature of impacted soils and ecosystems on mining footprints, the requirements of a rehabilitation plan should be clear and concise with attainable soil

and vegetation parameters or success criteria (Bell, 2002). To assume that success will be attained merely through the introduction of plant species and applying standard amelioration techniques in such an area could ultimately result in failure, financial loss and refusal of closure by the authorities (Mohr-Swart & Tanner, 2007). In the mining industry, most environmental activities are carried out by environmental managers employed by each mining company. Environmental managers must supply correct information and apply activities that are based on scientific results where possible. Rehabilitation has become an activity that includes human resources, equipment, available materials and correct land management processes that are both practical and theoretical.

Post-closure land uses that should be included in the rehabilitation activities must be clearly defined and should include the sustainable use of the environment in the long-term. Practical considerations for selecting the rehabilitation procedure include aspects such as the application of fertilisation techniques needed on certain TSFs and selection of the correct plant species, which includes, for example, the coating of seed that would potentially increase the germination and establishment potential of the species (Mohr-Swart & Tanner, 2007;). Rehabilitated sites should also be monitored to ensure the sustainability over the long-term (Hobbs & Harris, 2001).

According to ELD (2015), “sustainable land management practices are those that serve to maintain ecological resilience and the stability of ecosystem services indefinitely, while providing sustenance and diverse livelihoods for humans”. The complex system that forms sustainable land management includes different technological methodologies, practices and approaches. It aims to localise the management of land, which then positively impacts national and international spheres of land use (ELD, 2015).

As every system is dynamic, stakeholders on different levels are included who have to be informed, satisfied and who control financial availability or communal acceptance of proposed strategies (ELD, 2015). Sustainable land management impacts a range of factors, including people’s political, cultural and societal convictions, and therefore forms a critical part of a system that has to be placated to start achieving rehabilitation goals.

To fully understand the meaning of “environmental compliance”, a holistic look at the integral components thereof has to be taken. Then the depth of the statement (environmental compliance), becomes apparent, as does what a company/individual commits to when stating that compliance has been achieved (Azapagic, 2004).

Mine rehabilitation requires specific scientific research to produce new and innovative ways of legislative compliance and ultimately to reach mine closure. The former forms part of this study, namely to assess and study approaches currently available for gold and platinum TSF rehabilitation by contractors that intend to combine re-seeding with soil amelioration technologies. The use of innovative methods are illustrated in this study and there is an attempt to obtain successful rehabilitation procedures while reducing the impact on the disturbed environment surrounding mining activities and nearby communities in South Africa.

Chapter 2

Project overview

2.1 Background of study

This project formed part of a continuous research programme funded by AGT Foods Africa, previously known as Advance Seed. The company is situated in Krugersdorp, Gauteng province, South Africa, and has supported research projects regarding the use of coated and non-coated grass seed types for rehabilitation for a number of years. Research started during 2006/2007 by Ms Y Brits, who focussed on the effect of seed coating on seed establishment and root morphology (Brits, 2007). The study consisted of two trials, namely a pot trial in a greenhouse of the North-West University (NWU) in Potchefstroom and a field trial. The species used during this project included *Chloris gayana* (Rhodes grass), *Cynodon dactylon* (couch grass), *Digitaria eriantha* (common finger grass) and *Eragrostis curvula* (weeping love grass). The research yielded valuable results regarding above- and below-ground biomass yields, insect predation and information pertaining to the difference in vascular tissue of the transitional region of seedlings of coated and non-coated seed types (Brits, 2007).

Thereafter, the research was continued through the MSc. project of Ms M Westcott (Westcott, 2011). The objective of the study was to determine the effects of seed enhancement on the emergence and establishment of selected grass species in four different soil types (growth mediums) under controlled and non-controlled conditions (Westcott, 2011). The following grass species were used in this project: *Antheophora pubescens* (bottle brush grass), *Cynodon dactylon* and *Panicum maximum* (Guinea grass). Based on the results of this study, newly developed standards for seed coating were applied, including certified compilations of coating enhancements, which differed for each species.

The third MSc. project was carried out by Ms I Muller (Muller, 2014), who conducted research on five grass species in ten different growth mediums in pot trials in a

nursery at the North-West University (NWU), Potchefstroom campus (Muller, 2014). The species selected for the rehabilitation of mine tailings storage facilities (TSFs) were *Cenchrus ciliaris* (foxtail buffalo grass), *Chloris gayana* (Rhodes grass), *Cynodon dactylon*, *Digitaria eriantha* and *Eragrostis curvula*. The growth mediums used were mine tailings from andalusite, fluorspar, fine coal discard, gold <1% pyrite content, gold >2% pyrite content, gypsum, kimberlite and platinum. Red sandy soil from the Hutton soil form and vertic soil from the Arcadia soil form were used as controls. These growth mediums characterise the different growth mediums of the above TSFs in South Africa (Muller2014). The study focussed on the effect of the coating on the micro-morphology and water absorption of the seed, as well as the general germination and anatomical fluctuations according to the different mediums, coatings and species types (Muller, 2014).

The abovementioned studies and some outcomes are summarised in Chapter 4 of this dissertation. Although good data and results were obtained through these studies, it is important to assess the applicability of these grasses for rehabilitation under natural conditions as carried out by rehabilitation contractors at mining sites.

2.2 Project overview and objectives

Different industries, represented by mining, rehabilitation consulting and seed production/distribution companies are constantly working to produce new methods to enable rehabilitation of mine TSFs. These methods rely on proven scientific methods, which ultimately reduce cost, improve rehabilitation project reliability and provide a competitive advantage over current methods. The objective of this study was to build on previous nursery trials conducted by the post-graduate students of the NWU and to establish whether environmental factors influence the findings for application in the industry. The current phase of the research project differs from the previous work since no nursery trials were carried out during the 2015 growth season. Some nursery trials had to be carried out after access to the relevant platinum mines was denied in 2016 (see Chapter 4).

Previous research led to the hypothesis that the use of these species for rehabilitation of TSFs would be positive if studied under natural conditions.

2.3 General objectives

The main objectives of this study included the following:

- Summarising existing data from previous studies that assessed the germination, growth and establishment of selected grass species for rehabilitation.
- Assessing the germination and establishment of five coated and non-coated grass species used for the rehabilitation of gold and platinum TSFs in natural dryland conditions.
- Assessing the potential of selected coated and non-coated grass species commonly used in gold and platinum TSF rehabilitation.
- Assessing the impact of soil amelioration techniques on the chemical composition of the soil in gold and platinum TSF rehabilitation.

This study therefore extended the work done previously by the NWU to test the results obtained under natural dryland conditions.

2.4 Specific objectives

The specific objectives of the study were:

- To assess the germination of coated and non-coated seed of *Cynodon dactylon*, *Eragrostis curvula*, *Eragrostis tef*, *Medicago sativa* (lucerne/alfalfa) and *Sorghum* sp. on gold and platinum TSFs.
- To assess the germination and establishment of the selected species on slopes and flat sites of gold and platinum TSFs.
- To compare the re-growth potential of the selected species through surveys and observations.
- To assess the impact of mulch on the germination of the selected species.
- To propose preferred species for rehabilitation of gold and platinum TSFs.
- To analyse the fluctuations and impacts of soil pH and mineral composition on vegetation growth over time.

2.5 Dissertation structure and content

The main focus of the dissertation is the establishment of scientific research to prove the value of coated vs. non-coated seed for rehabilitation. The dissertation attempts to prove that when compared, coated seed have higher yields, faster establishment rates and greater rates of success when compared to non-coated seed in dryland conditions.

The dissertation is structured as follows:

Chapter 1 contains the literature review, where literature regarding rehabilitation practice, legislation and the scientific process regarding the research conducted is discussed.

Chapter 2 includes the introduction and discusses the background and objectives of the study.

Chapter 3 provides a summary of previous applicable research (funded by AGT Foods) of coated and non-coated seed and the results of these studies as well as comparisons made.

Chapter 4 provides the reader with an in-depth background of the study sites, the geological, floral and climatic conditions and the methods used for data collection.

Chapter 5 assesses the results obtained and discusses the outcomes in relation to the study aims and objectives.

Chapter 6 provides a holistic conclusion and provides recommendations for future research.

Chapter 7 includes the references used for the purpose of this study.

Chapter 3

Review and summary of previous research

3.1 General

The collaboration between AGT Foods Africa (Pty) Ltd³ (henceforth AGT Foods Africa) and the North-West University (NWU) has delivered extensive research results since 2007. The continuous financial and professional assistance from AGT Foods Africa has led to the completion and publication of four MSc. studies. A summary of the results of the previous four master's studies that lead to this study are discussed to provide a holistic overview of the history of coated and non-coated seed research as prescribed and discussed with AGT Foods Africa. The influence of these results on the approach of the study completed for this dissertation will also be mentioned.

Three of the previous studies were completed at the NWU in 2007, 2011 and 2014 and include:

1. "A comparison of selected enhanced (coated) and non-enhanced grass seed types for re-seeding of disturbed areas" by Ms Y Brits (2007), NWU, Potchefstroom (Brits, 2007).
2. "An evaluation of the germination and establishment of three selected coated grass species in different soil types for rehabilitation" by Ms M Westcott (2011), NWU, Potchefstroom (Westcott, 2011).
3. "Seed viability and regrowth of grasses used for mine waste rehabilitation" by Ms I Muller (2014), NWU, Potchefstroom (Muller, 2014).

The research completed followed a structured approach to enable valuable knowledge regarding seed coating for plant species used on degraded and disturbed

³ AGT Foods Africa (Pty) Ltd
8 Jacobs street, Chamdor
Krugersdorp.

areas and for mine tailings storage facility (TSF) rehabilitation. It combined knowledge and experience from industry specialists in rehabilitation, especially from AGT Foods Africa and rehabilitation contractors with academic knowledge offered by the NWU.

Additionally, research conducted at the University of Pretoria by Ms Leana Nel in 2013 was also considered in the present study. Nel's (2013) study considered the role of seed coating in the establishment and growth of *Medicago sativa* L. cultivars (Nel, 2013). Her study shed valuable light on the germination potential, growth and survival of *M. sativa*, as well as the cultivars chosen for this study.

The aims and objectives of each project are briefly discussed, followed by the results, a brief discussion and how it was used as background knowledge for the present study.

3.2 Research objectives of previous research projects

3.2.1. Brits (2007)

Brits (2007) investigated the increase in germination potential and the establishment, growth percentages and biomass yield of different grass species.

This was achieved by specifically comparing coated and non-coated grass species seed in terms of the following:

- Germination and establishment percentages.
- Comparison of above- and below-ground biomass yield in two different growth mediums in a greenhouse of the NWU;
- Evaluation and comparison of ant and small insect predation in a field trial; and
- Comparison of vascular tissue structural differences in the transition root region of seedlings.

The study included laboratory, greenhouse and field trials to enable a full range of results. Grass species that were chosen for the study included *Chloris gayana*, *Cynodon dactylon*, *Digitaria eriantha* and *Eragrostis curvula*.

3.2.2. Westcott (2011)

Westcott (2011) investigated the effect of seed coating on three grass species commonly used in the rehabilitation of mine TSFs and degraded, natural rangelands, namely *Antheophora pubescens*, *Cynodon dactylon* and *Panicum maximum*. The study focussed on the germination and establishment rates of these species in four growth mediums, namely sandy, clayey, acidic and alkaline soil types. The study also focussed on the benefits, possible impacts and reactions of the seed of the abovementioned grass species when used for rehabilitation in the different growth mediums. Furthermore, enzyme reaction and activity during germination and the influence of water content in seed growth and survival were studied. A comparison between coated and non-coated seed was carried out for all the objectives.

Research was subsequently carried out in laboratory, greenhouse (controlled conditions) and field trials under natural conditions. No soil amelioration was applied on gold and platinum TSFs near Stilfontein and Rustenburg in the North-West province, where the field trials were conducted.

3.2.3 Muller (2014)

Muller (2014) continued the research conducted by Westcott (2011) by investigating the second-generation success of coated and non-coated grass seed in different growth mediums. Growth mediums of eight different mine TSFs and two control soil mediums were used in this study to evaluate progeny seed, the impact of soil mediums on second-generation germination (i.e. whether the seed produced by the primary/first plants grown in the medium were still viable), general growth and the evaluation of above-ground re-growth after cutting. Grass species suitable for the rehabilitation of different growth mediums collected at the TSFs were also identified. The species used in this study included: *Eragrostis curvula*; *Eragrostis tef*; *Cenchrus ciliaris*; *Digitaria eriantha*; *Cynodon dactylon*; *Chloris gayana*; *Hyparrhenia hirta*; and *Sorghum bicolor*.

3.2.4 Nel (2013)

The fourth study carried out by Nel (2013) focussed on the influence of seed coating specifically on lucerne (*Medicago sativa* – Super Cuf and SA Standard cultivars). The focus was on germination, emergence, seedling growth parameters and seasonal yields in optimal and sub optimal conditions. The conditions enforced on the seedlings involved variables such as high salinity levels and different growth mediums. To achieve the results, germination tests were conducted using conventional germination methods such as the “top-of paper” method according to the International Rules for Seed Testing (2006) as produced by the International Seed Testing Association. The following comparisons were drawn:

- The Jacobsen method vs. the use of Petri dishes.
- The effect of a nutrient-available environment vs. that of a nutrient-deficient environment.

Furthermore, variables such as osmotic potential, salinity (and the effect of electrical conductivity) were included.

3.3 Results

The results and conclusions of each project are summarised in the tables below.

Table 3.1: Results and conclusions drawn by Brits (2007).

Factor	Soil and environment	Species	Coated seed (germination percentage)	Non-coated seed (germination percentage)	Comments
Germination: dormancy breaking treatment (potassium nitrate (KNO³)) and pre-chilled at 5°C.	N/A	<i>Chloris gayana</i>	12%	28%	Significant variation
	N/A	<i>Cynodon dactylon</i>	17%	7%	Significant variation
	N/A	<i>Digitaria eriantha</i>	-	-	Difference not significant
	N/A	<i>Eragrostis curvula</i>	-	-	Difference not significant
Germination without dormancy breaking	N/A	<i>C. dactylon</i>	5%	16%	Significant variation
	N/A	<i>E. curvula</i>	63% (organic insecticide on base of coat and overspray)	45%	Significant variation
	N/A	<i>E. curvula</i>	9% (plain coating)	48%	Significant variation
	N/A	<i>D. eriantha</i>	32%	24%	Not significant
Seed germination testing results differ between North-West University (NWU) and AGT Foods Africa (AGT)	N/A	<i>D. eriantha</i>	NWU – 22% AGT – 33%	NWU – 32% AGT – 23%	Differing germination results could be due to testing dates and dormancy changes over time. Storing methods (temperature changes, transportation) influence germination percentages.
	N/A	<i>C. gayana</i>	NWU – 30% AGT – 27%	NWU – 34% AGT – 32%	
	N/A	<i>C. dactylon</i>	NWU – 5% AGT – 70%	NWU – 15% AGT – 75%	
	N/A	<i>E. curvula</i>	NWU – 9% AGT – 51%	NWU – 45% AGT – 74%	
Glasshouse trials: establishment	Hygromix	<i>D. eriantha</i>	32%	9%	Species established in Hygromix delivered better biomass yield.
		<i>E. curvula</i> (OIOBOC)*	51%	p <0.001	
		<i>C. gayana</i>	16%	19%	
	Coco peat moss	<i>C. dactylon</i>	21%	37%	
		<i>D. eriantha</i>	26%	13%	
		<i>E. curvula</i> (OIOBOC)*	60%	Difference of p<0.001	
Biomass production		<i>C. gayana</i>	Higher above- and below-ground biomass (dry)	Higher above – and below ground biomass (Fresh)	
		<i>C. dactylon</i>	Higher above- and below-ground biomass (fresh)	Higher above- and below-ground biomass (dry)	
		<i>D. eriantha</i>	Higher above- and below-ground biomass (fresh)	Higher above- and below-ground biomass (dry)	
		<i>E. curvula</i>	Higher above- and below-	Higher above- and below-ground biomass (dry)	

			ground biomass (fresh)		
		<i>C. gayana</i>			
		<i>C. dactylon</i>			
		<i>D. eriantha</i>			
		<i>E. curvula</i>			
Field trials: surveys after 9-month growing period.	Density	<i>C. gayana</i>	27 plants per m ²	11 plants per m ²	
		<i>C. dactylon</i>	34 plants per m ²	8 plants per m ²	
		<i>D. eriantha</i>	14 plants per m ²	23 plants per m ²	
		<i>E. curvula</i> (OIOBOC*)	60 plants per m ²	55 plants per m ²	
	Frequency	<i>C. gayana</i>	87%	70%	
		<i>C. dactylon</i>	91%	63%	
		<i>D. eriantha</i>	68%	78%	
		<i>E. curvula</i>	84%	94%	

*OIOBOC: organic insecticide on base of coat

Establishment of plants in greenhouse trials was calculated after seven weeks. All of the abovementioned species were planted in a Hygromix and/or coco peat moss mixture to simulate plant growth. Species planted in coco peat moss only reached a juvenile stage and thereafter stopped producing noticeable biomass. The study showed that the Hygromix mixture provided sufficient nutrients for growth and therefore delivered higher biomass except for coated and non-coated *C. gayana* and *E. curvula*. In both mediums, non-coated *C. dactylon* and *E. curvula* established significantly better although not producing higher biomass in the case of *E. curvula*. The overall establishment of the *D. eriantha* and *E. curvula* seed that were encapsulated with a special coating, namely organic insecticide on base of coat (OIOBOC), was overall higher (Table 3.1).

The only significant difference in terms of dry above-ground biomass was noted with *D. eriantha* non-coated seedlings, which yielded a much higher value than the coated seedling of the same species. The coated *C. gayana* seedlings were the only species that yielded a higher fresh and dry, above-and below-ground biomass in the greenhouse trials. Results further showed that non-coated *E. curvula* had higher levels of available protein and nutrients. The higher values for grasses tested in

greenhouse trials, where the Hygromix and/or coco peat moss mixtures were used to stimulate the growth, could, however, not be ascribed to the coating of the seed and this was therefore not considered. In the field trials, coated-seed grass species had an overall higher density, except for *D. eriantha*, which showed higher results for non-coated seed of the same species.

Significant differences in frequency were found with *C. dactylon* coated seed, which resulted in a much higher average than non-coated seed. When comparing average density with average frequency, specific trends were observed for all the seed types except for *E. curvula* seed (coated with OIOBOC), which had the highest density overall. Non-coated *E. curvula* seed had the highest frequency, whereas the coated seed of the other trial species had the same average frequency.

Results showed that *C. gayana* coated seed resulted in higher density and frequencies than non-coated seed, but had a lower average basal cover. This can be ascribed to the growth form of this species, which does not make large tufts but is a stoloniferous plant. It therefore spreads well and normally acts as a soil stabiliser. Results also showed that plots sown with OIOBOC seed had the highest density and the same frequency as the rest of the treatments but had the lowest basal cover overall.

The species were classified according to their importance value (IV), based on the sum of the relative density, relative frequency and relative basal cover. The rankings showed that non-coated *E. curvula* seed scored the highest IV ranking, followed by coated *E. curvula* (OIOBOC) and coated *E. curvula* (OIOBOC). It was therefore recommended that this species be used in re-seeding practices in the rehabilitation process.

Seed predation results showed that a minimum seed predation (less than 1%) took place in the trials. Coated *C. gayana*, *C. dactylon* and *E. curvula* seed showed lower predation percentages than non-coated seed of the same species. On the other hand, non-coated *D. eriantha* seed showed lower seed predation than coated seed of this species. Results for seed predation trials were used to propose further research into this topic.

Table 3.2: Results and conclusions drawn by Westcott (2011).

Factor	Species	Soil and environment	Coated seed	Non-coated seed	Comments
Germination and establishment	<i>Antheophora pubescens</i>	Greenhouse (all four soil types)		Faster germination in all four soil mediums. Better germination in sandy, well-drained soils such as gold and platinum tailings. Seven days – maximum germination percentage. Water retention capacity plays major role, no competition and irrigation ensures adequate moisture in growth zone of sandy soils.	
	<i>Cynodon dactylon</i>	Greenhouse (all four soil types)	Initial emergence lower than that of non-coated seed but recovered to exceed that of non-coated seed.		Both seed types – low germination in clayey soil as well as gold and platinum tailings. Germination and establishment of both seed types also lowest in clayey soil under uncontrolled conditions, possibly due to predation.
	<i>Panicum maximum</i>	Greenhouse (all four soil types)	Low overall germination success.	Low overall germination success.	Prefers soil types with high water holding capacity and less drainage. Hygroscopic properties of lime in coated seed led to better growth in sandy soils. Performs better in mine soils with no rivals/competitors in seedbank.
Peroxidase (POD)	All three species			Average POD activity higher than that of coated seed.	<i>P. maximum</i> and <i>C. dactylon</i> showed decrease in POD activity after first coating process.
Alpha amylase (α -amylase)			<i>P. maximum</i> and <i>C. dactylon</i> showed higher α -amylase levels two days after germination, thus showing that the germination process is better initiated.	After 10 days, α -amylase levels in uncoated seed are higher, possibly due to starch depletion in coated seed due to quicker initiation of germination.	
Lipoxygenase			Higher germination metabolism than non-coated seed.		
Relative water content			<i>A. pubescens</i> showed improved relative water uptake and content, which points positively toward successful germination.		

Competition plays a major part in germination and establishment of seedlings. The study found that uncontrolled sites under natural/field trial conditions (on gold and platinum TSFs) with existing seedbeds and no soil amelioration changed the establishment rates for the different species because of competition. Generally, seed that germinated the fastest (e.g. *A. pubescens*) out-competed other species, such as *C. dactylon* and *P. maximum*, which would influence what type of species to choose in a rehabilitation plan (Table 3.2). Therefore, higher sowing rates could be required for certain species, as well as the use of herbicides to eradicate unwanted vegetation that might compete with the grass seed sown. Germination and establishment of the seedlings in the field trials were also low, because no amelioration was applied.

An important general observation from this study showed that results (germination and establishment) were potentially influenced in greenhouse (controlled) studies because of the combination of substrate wetness and lower average temperatures. This could have impaired seedling germination and influenced optimal oxygen uptake, which influenced results for all species in this study. External effects affect seed germination and thus seed coating cannot be seen in isolation, but has to be adapted to be more species-specific, as individual tolerance levels to external factors for different species may vary.

Low germination percentages of species were not caused by the dormancy of the seed, but rather by physiological constraints within seed due to periodic water uptake during the coating process. It was determined that seed coating could have a stimulating effect on the germination metabolism of the selected trial grass species. The physiological results of the study showed that purity of seed batches does not necessarily imply high quality of the seed themselves. The higher values of germination metabolism in coated seed was reflected in the higher enzyme activity of the three germination enzymes. Therefore, seed coating stimulates germination metabolism. However, this effect only lasts for a specific time. Thereafter, stored energy is depleted and the oxidising enzymes cause loss of viability.

Table 3.3: Results and conclusions drawn by Muller (2014).

Factor	Species	General comment
Germination of progeny seed	<i>Eragrostis curvula</i>	The study found that a general rise in saturated electrical conductivity (EC) of the growth medium was accompanied by a proportional rise in germination of this species. Overall, this species showed positive results for progeny seed production and showed why it is chosen for many rehabilitation sites.
	<i>Cynodon dactylon</i>	A rise in fluorine (f) leads to a proportional rise in progeny seed germination. Similarly, low pH values, which lead to a low net acid potential and higher aluminium values, had a negative effect on germination of progeny seed. Overall results showed that this species produced viable progeny seed but was sensitive to aluminium toxicity.
	<i>Chloris gayana</i>	As with <i>E. curvula</i> , the study found that a general rise in saturated EC of the growth medium was accompanied by a proportional rise in germination of this species. Low germination results for all growth mediums except for platinum tailings showed that this species had relatively low vigour and was easily affected by poor soil conditions such as those used during this study.
	<i>Cenchrus ciliaris</i>	Again, a general rise in saturated EC of the growth medium was accompanied by a proportional rise in germination of this species along with higher levels of sulphur S. <i>Cenchrus ciliaris</i> is commonly used for erosion control and is able to withstand the impacts associated with rehabilitation/poor soil mediums, but this study showed that it would require monitoring and management of essential nutrients to enable optimal viability of progeny seed.
	<i>Digitaria eriantha</i>	The f content in the growth medium showed the only increase in germination potential but similar negative impacts were recorded as was done for <i>C. dactylon</i> . The results indicated that low pH levels and nutrient deficient soils impacted the viability of the progeny seed but not to such an extent as to be classified as a high impact. Results nonetheless varied between growth mediums and <i>D. eriantha</i> is considered to be viable for rehabilitation use.
	<i>Sorghum bicolor</i>	<i>Sorghum bicolor</i> showed a negative reaction to a decrease in pH but an increase in Al content produced positive results. During the study it was found that many green seed were produced that could be considered non-viable, but overall results showed that <i>S. bicolor</i> is a viable choice for rehabilitation efforts.
	<i>Eragrostis tef</i>	The growth medium showed limited impact on the germination of <i>E. tef</i> , but an increase in nitrate levels led to improved progeny seed germination results. Viable seed germination and growth indicated that <i>E. tef</i> was not adversely affected by growth medium conditions, it also responded positively to nitrate concentrations improvements This species also showed the only negative results after re-cutting commenced, which can be ascribed to the fact that it is a perennial species and had completed its lifecycle.
	<i>Hyparrhenia hirta</i>	Results showed that progeny seed were possibly harvested too early (no guidelines exist for this species), thus impacting the germination results. No conclusions could be drawn.

Research by Muller (2014) confirmed what Brits (2007) found, namely that the seed coating retains water, which is favourable for seed sown in growth mediums with poor water retention, such as kimberlite and fluorspar tailings deposits. Coating ingredients could also generate a negative charge on the seed coating, which further reduced water availability.

Results showed that the growth mediums (eight different mine TSFs and two soils – vertic and red) influenced the germination of coated species mostly due to water retention and geo-chemical characteristics, although coated seed of *Cenchrus ciliaris*, *C. dactylon*, *C. gayana*, *D. eriantha* and *E. curvula*, achieved higher germination results in kimberlite, fluorspar, gold (>2% pyrite), vertic soils and red

sandy soil. When mulch (organic matter cover) was used in the seeding method, it benefitted the growth of the species, except for *C. gayana* and *D. eriantha* in kimberlite tailings. Under certain physical constraints of the growth medium, coated seed did not show improved germination percentages compared with non-coated seed.

Results by Muller (2014) further showed that a high pyrite content in gold tailings material and low pH led to availability of a high level of aluminium and high net acid potential, which influenced the survival of the grass species used for the trial. The inherent cost of lime fertiliser applications, which have to be implemented to remedy the imbalance in acid rich soils, was also very high.

Progeny seed were harvested separately from the parent grasses and for each growth medium. The germination rate and percentages were then correlated with the initial germination results to obtain viability. *Eragrostis curvula* achieved very high (90%) viability and was deemed a successful producer of progeny seed. *Cynodon dactylon* progeny seed germinated very well, especially in the andalusite trials (70%). On the other hand, *C. gayana* achieved an overall low percentage of germination in all growth mediums except platinum (90%) and this confirmed the available research of poor viability in progeny seed for this species.

Table 3.4: Results and conclusions drawn by Nel (2013).

Factor	Species	Test method	Coated seed	Non-coated seed	Comments
Germination	<i>Medicago sativa</i> Super Cuf	Standard germination test – “top of paper”		Higher germination percentage than coated seed.	The suggestion was made that this cultivar is more sensitive to the coating process; distinction between inhibition and delay could not be made because of time constraints.
	<i>M. sativa</i> SA Standard		No statistical difference between coated and non-coated seed after 4 and 10 days.	No statistical difference between coated and non-coated seed after 4 and 10 days.	Coating does not influence SA Standard germination
	<i>M. sativa</i> Super Cuf	Petri-dish method		Non-coated seed germination percentages appeared higher, although statistically small.	A negative effect on germination was shown using this method, possibly due to lower oxygen concentrations.
	<i>M. sativa</i> SA Standard		Coated seed germination percentages appeared higher, although statistically small.		This method appeared flawed in the sense that conditions in a petri-dish differ significantly from natural conditions (e.g. water and chemical retention/exposure)
	<i>M. sativa</i> Super Cuf	Jacobsen table method		Non-coated seed germination percentages appeared higher, although statistically small.	The coating contributed to imbibition diluting the inhibitor increased germination percentages for both seed types.
	<i>M. sativa</i> SA Standard		Coated seed germination percentages appeared higher, although statistically small.		

From the above study and results regarding osmotic potential and salinity experiments, it was found that the *M. sativa* Super Cuf cultivar is more sensitive to its surrounding environment than the SA Standard cultivar. This was caused by the lower imbibition rate, also allowing higher germination rates under different saline conditions.

Results further indicated that both cultivars reacted differently to the interaction between coating, growth medium and saline conditions. Coated seed appeared to provide seed with necessary nutrients to overcome the nutrient deficiency in growth mediums and differences in water quality, especially where salinity influences the seed-soil environment and overall germination. The cultivars responded differently

according to physio-morphological methods and conditions (temperature, water availability), indicating that plant genetic capabilities, rather than coating, enable seed to react differently in terms of germination, establishment, growth and percentage yield.

Seed coating had a limited effect on biomass yield for both cultivars, but serves as an effortless solution to farmers who need to include inoculants with the seed coating.

Recommendations from this research include that coated seed is considered favourable for saline conditions, especially in sodium chloride (NaCl)-rich mediums, but that further genetic research is needed if the two cultivars are compared, especially regarding coating requirements.

3.4 Summary of all results

As part of the present study, the following critical results are additionally summarised (Table 3.5) from the work completed at both universities mentioned above.

Table 3.5: Critical results from the four studies.

	Coated seed	Non-coated seed	Organic insecticide on the base and as overspray
Germination percentage	<i>Digitaria eriantha</i> <i>Eragrostis curvula</i> <i>Cynodon dactylon</i> (controlled conditions: sandy soil, clayey, gold mine tailings, platinum tailings)	<i>Chloris gayana</i> <i>C. dactylon</i> , <i>Anthephora pubescens</i> (controlled conditions) <i>Panicum maximum</i> ,	
Seed purity	<i>C. gayana</i> , <i>E. curvula</i>	<i>C. dactylon</i> , <i>D. eriantha</i> , <i>E. curvula</i>	
Biomass production (controlled conditions)	<i>C. gayana</i>	<i>C. dactylon</i> , <i>D. eriantha</i> , <i>E. curvula</i>	<i>E. curvula</i> in terms of fresh below-ground biomass
Field trial (biomass, density, frequency)	<i>C. gayana</i> , <i>C. dactylon</i>	<i>D. eriantha</i>	<i>E. curvula</i>
Basal cover (field trial)	<i>C. dactylon</i>	<i>C. gayana</i> , <i>D. eriantha</i> , <i>E. curvula</i>	
Weed frequency	<i>D. eriantha</i>	<i>C. gayana</i> , <i>C. dactylon</i> ,	<i>E. curvula</i>
Seed predation	<i>D. eriantha</i>	<i>C. gayana</i> , <i>C. dactylon</i> , <i>E. curvula</i>	

Recommendation for use in natural field environment	<i>C. gayana</i> <i>C. dactylon</i>	<i>E. curvula</i> , <i>D. eriantha</i>	<i>E. curvula</i>
Mulch benefits all species – enhanced/non-enhanced	✓	✓	
Water retainment	Positive – seed sown in growth mediums with poor water retention, such as kimberlite and fluorspar tailings deposits. Negative – water not available to seed, captured in coating, poor germination.		

The research completed since 2011 has focussed on the availability of coating nutrients and water as well as the germination, growth and re-growth of a variety of species commonly used for rangeland and mine TSF rehabilitation.

Most of the research by previous studies was carried out in pot and greenhouse trials. Although valuable, these results had to be tested in field trials under natural conditions. It was therefore decided to carry out trials of selected grass species and lucerne cultivars used in the above research and evaluate their germination and growth on gold and platinum mine TSFs in this study. The results of all studies should then add to better rehabilitation practices and seed marketing strategies in terms of mine rehabilitation. Previous results were also used to guide decisions regarding sowing density applications, soil amelioration and collection of field data necessary to obtain results under natural conditions. Results from the field trials carried out for this study were expected to confirm previous recommendations that seed coating can be efficient and add to survival, germination and growth potential of species, but that species-specific coatings should be considered for improved mine TSF rehabilitation results.

Chapter 4

Materials and methods

4.1 Study site location

A partnership was initiated with Agreenco Environmental Projects in Potchefstroom⁴, South Africa. As a major contributor to mine rehabilitation, Agreenco Environmental Projects possess the knowledge and resources to assist with trial site identification, access, provision of equipment and required materials for rehabilitation establishment. An agreement was reached over the location and availability of sites. The following three sites were chosen for the study (Figure 4.1; Table 4.1):

- Anglo Platinum Paardekraal mine in Rustenburg, North-West province.
- Crown gold mine (Mooifontein TSF) in Johannesburg, Gauteng province.
- Rooikraal gold mine (TSF) in the Nigel area, Gauteng province.
- North-West University (NWU) nursery - platinum bulk bags, Potchefstroom, North-West province.

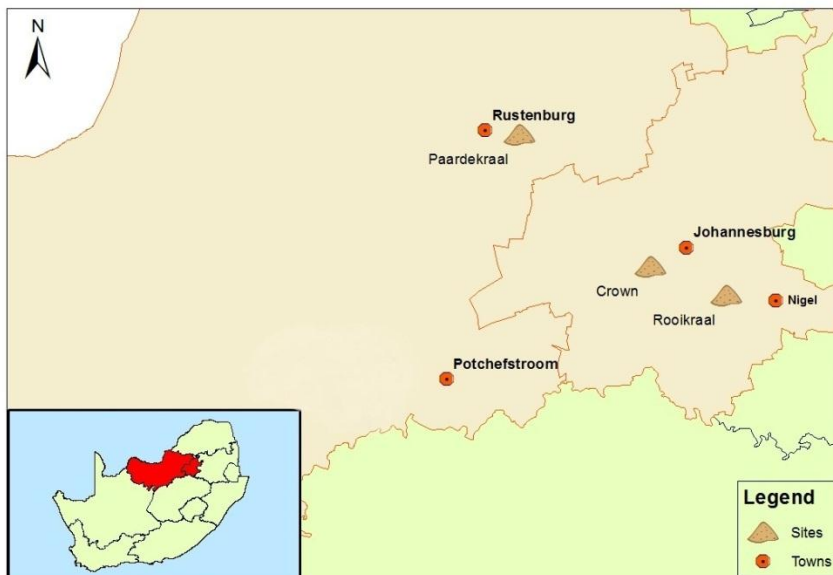


Figure 4.1: Study site locations of gold (Crown and Rooikraal) and platinum (Paardekraal and Potchefstroom -NWU) mines in collaboration with Agreenco Environmental Projects.

⁴Holdings 467, Vyfhoek, Potchefstroom, 2531; PO Box 19896, Noordbrug, 2522.

Table 4.1: Study site global positioning system (GPS) coordinates.

Site	Location	GPS coordinates
Gold TSF	Crown, Johannesburg South	26°14'37.66"S; 27°58'3.39"E
Gold TSF	Rooikraal, Nigel	26°21'19.64"S; 28°17'23.60"E
Platinum TSF	Paardekraal, Rustenburg	25°37'59.50"S; 27°19'13.96"E
Platinum bulk bags	NWU Potchefstroom	26°40'52.44"S; 27°5'50.37"E

4.2 Rustenburg (Paardekraal TSF)

This study site is situated near Rustenburg, at the Paardekraal platinum tailings storage facility (TSF) in the North-West province, South Africa (Figure 4.1).

4.2.1 Trial location

The six trial plots were situated at Paardekraal operational platinum mine outside of Rustenburg. The Paardekraal mine TSF is under rehabilitation by Agreenco and Fraser Alexander and therefore only sloped areas were used as trials for this project.

4.2.2 Vegetation

This study area falls within the Central Bushveld bioregion of the Savanna biome. According to Mucina and Rutherford (2006), the Savanna biome in and around Rustenburg comprises mainly the Gold Reef Mountain Bushveld, Moot Plains Bushveld, Marikana Thornveld, Norite Koppies Bushveld, Central Sandy Bushveld, Rand Highveld Grassland and the Zeerust Thornveld. The area is characterised by rolling hills, plains and granite koppies, although some minor mountain ranges do occur (altitude varies between 1050 and 1450 m). The area surrounding Rustenburg is well suited for dry-land agriculture with well-established below-ground water

reservoirs and suitable climate and rainfall. The study site falls directly within the Marikana Thornveld, which is characterised by open *Vachellia karroo* (formerly *Acacia karroo*) woodland that commonly contains various woody species such as *V. burkei* and *V. caffra*, as well as small tree species such as *Ziziphus mucronata* and *Celtis africana*. Dense shrubs (*Olea europaea*, *Grewia flava*) also occur along drainage lines and where protected from fire by rocky outcrops (Mucina & Rutherford, 2006).

4.2.3 Climate

Rustenburg is situated in an average warm temperate region with seasonal summer rainfall (October–April) and dry winters. The Bushveld region is commonly known for sporadic thunderstorms and receives annual precipitation of 600–700 mm. Frost is fairly frequent in winter, but as with rainfall, can vary dramatically in abundance and occurrence from year to year. The area enjoys a mean annual sub-tropical temperature of 16–35°C but can experience extremes of up to 45°C during summer (Mucina & Rutherford, 2006).

4.2.4 Historical average rainfall and temperature

Figure 4.2 indicates the average rainfall and temperature experienced in Rustenburg over a growth season. With 18 rainfall days on average per month from November to January and more than 10 rainfall days per month during the rest of the growth season, plant establishment is generally more certain than what was experienced during the growth season of 2014–2015 specifically at this site, where rainfall was reported to be less than 30 mm for the entire season.

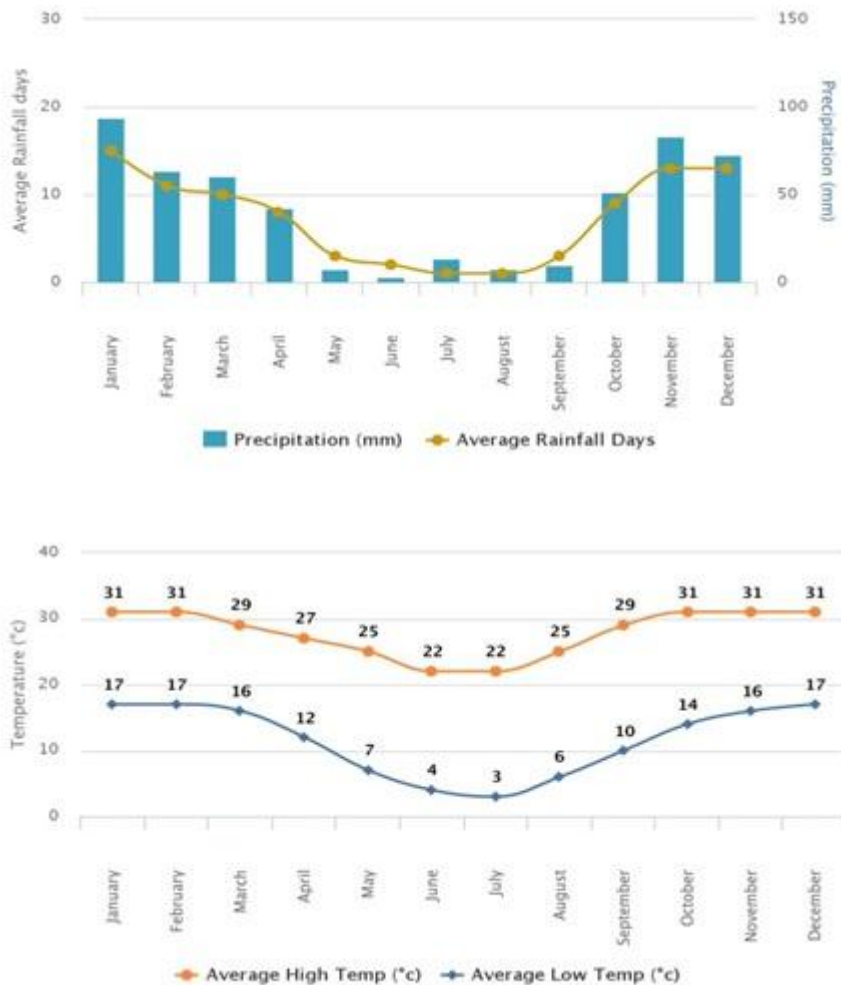


Figure 4.2: Rustenburg historical rainfall and temperature data (10 year average) (www.worldweatheronline.com date of access: 12 June 2016)

During 2016, the platinum trial sites became unavailable at Paardekraal TSF due to unforeseen changes in mine ownership. The decision was then made by the project team to continue trials in platinum TSF material at the NWU, Potchefstroom campus nursery under simulated dryland conditions in bulk bags. This ensured continuity of survey data and a valuable comparison between the nursery and TSF plots. Soil collected at the study site was placed in six 1 m² bulk bags containing platinum tailings. The bulk bags were placed under limited water supply to simulate natural rainfall. This enabled the study to continue during the drought experienced during 2015/2016 as well as enabling easy access to the trials.

Potchefstroom experienced higher average temperatures during 2015 and 2016 with lower rainfall during the normal rainy season, followed by heavy rainfall during

specific months such as March 2016, when extremely high rainfall percentages and number of rainfall days (approximately 200 mm for March alone) were recorded for Potchefstroom, Johannesburg and Nigel. Specific rainfall and temperature data is discussed in Chapter 5 (South African Weather Service, 2016).

4.2.5 Geology and soil

The Paardekraal study site forms part of the Bushveld Igneous Complex (Figure 4.3) that was created by an eruption of one million cubic kilometres of magma. As the magma cooled, different layers of minerals solidified and was later classified, studied and are mined to this day. The platinum group elements of the Bushveld Complex are mined from the following reefs: Merensky, UG2 Chromatite and the Plat reef, which combine to form the Rustenburg Layered Suite (RLS) (Cawthorn, 2010). The RLS forms one of the world’s largest layered intrusions, consisting of an area of 300 by 400 km, with an approximate depth/thickness of 7–8 km. It consists mostly of gabbro, norite, pyroxenite and anorthosite rock formations and soils consist of vertic and melanic clays as well as some freely drained, deep soils (Mucina & Rutherford, 2006). According to Barnes and Maier (2002), the RLS contains 75% of the world’s platinum resources.

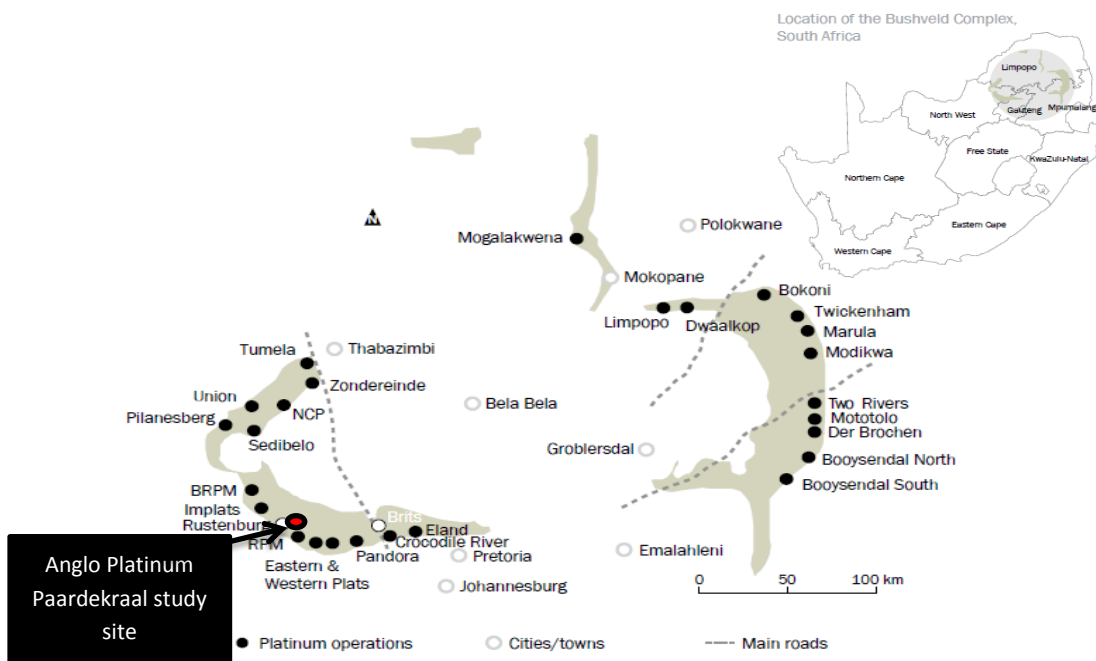


Figure 4.3: Location and layout of the Bushveld Igneous complex with the location of the Paardekraal study site.

4.2.6 Trial layout and plot description

Paardekraal trials consisted of sloped plots of 216 m² (six plots of 36 m² each) and the NWU nursery trials consisted of six 1 m² bulk bags (Figure 4.4 and Table 4.2).

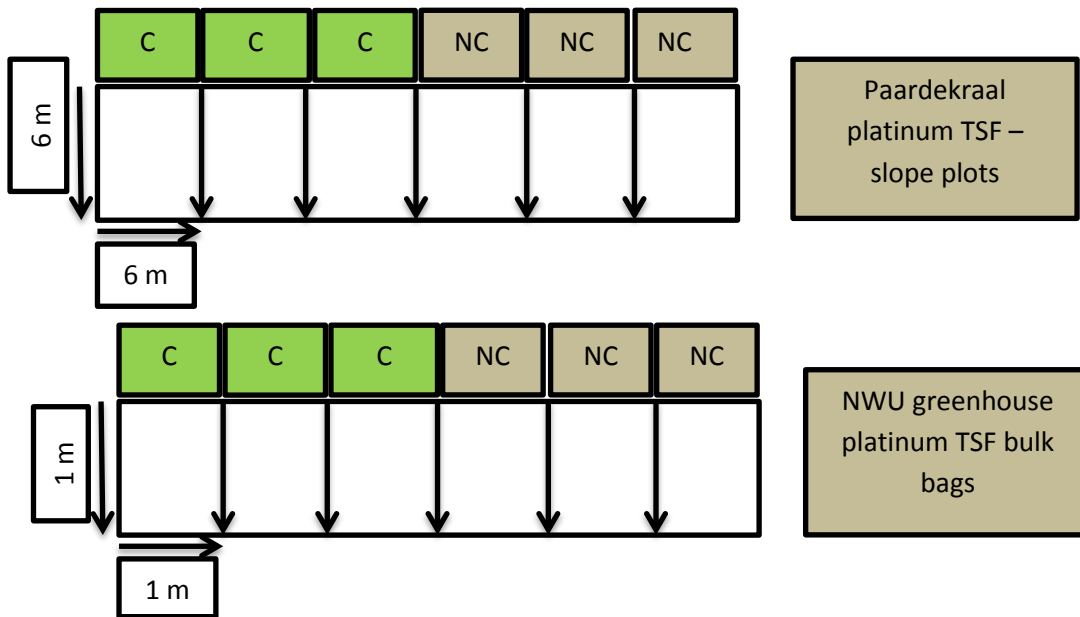


Figure 4.4: Field trial layout for Paardekraal platinum mine tailings storage facility (TSF) and layout for North-West University (NWU) greenhouse trials. C: coated seed; NC: non-coated seed.

Table 4.2: Description of trial plots at Paardekraal platinum mine tailings storage facility (TSF) and the North-West University (NWU) nursery. C: coated seed; NC: non-coated seed.

Paardekraal platinum TSF – slope plots	6 x 6 m – Three plot repetitions each of C and NC.	Alkaline, fine dark platinum spoil.	25°38'04.5"S; 27°19'22.2"E	C and NC – <i>Eragrostis curvula</i> , <i>Cynodon dactylon</i> , <i>Medicago sativa</i> , <i>Sorghum</i> sp.
NWU nursery platinum TSF – flat plots	1 x 1 m – Bulk bags; three plot repetitions each of C and NC	Alkaline, fine dark platinum spoil.	26°40'52.31"S; 27°5'50.46"E	C and NC – <i>E. curvula</i> , <i>C. dactylon</i> , <i>M. sativa</i> , <i>Sorghum</i> sp.

4.3 Johannesburg (Crown TSF)

4.3.1 Trial location

The study site is situated near Soweto, Gauteng province (Figure 4.1). The Mooifontein (Crown) gold TSF is situated in the Gauteng province within the Grassland biome. This biome is diverse in species composition and consists of predominantly C4 grass species, geophytes and some shrubs and trees (Mucina & Rutherford, 2006).

Mooifontein TSF forms part of the Crown gold mine suite of TSFs (Mooifontein, Nasrec and Diepkloof) situated adjacent to the N1-North in Soweto (Figure 4.1). The TSFs are situated adjacent to residential areas and the First National Bank Stadium (or Soccer City). The area is part of the Witwatersrand and the TSFs form part of a semi-circular ring of historical gold mines along what used to be the southern limit of Johannesburg. Rehabilitation is currently in its operational phase through Agreenco Environmental Projects.

4.3.2 Vegetation

Grass species are divided into sweet, low-fibre, highly palatable species and sour, high-fibre, unpalatable species. The biome further consists of plains and rolling hills and varies in height above sea level from almost at sea level to 2850 m above sea level at its highest point. The Grassland biome is influenced by urbanisation and especially industrialisation (mining). Large areas are also covered by commercial farming enterprises, specifically maize, but also sorghum, wheat and sunflower (Mucina & Rutherford, 2006).

The study site is situated on the Highveld plateau within the Soweto Highveld Grassland Bioregion. It is characterised by a moderately undulating landscape with medium-high, dense tufted grasses. Species commonly found in this bioregion are *Elionurus muticus*, *Eragrostis racemosa*, *Heteropogon contortus* and *Themeda triandra* and a variety of other grass species. The area also consists of occasional rock outcroppings and small wetlands, but disturbances such as industrialisation

have impacted greatly on the composition and interface between natural and built environment of the area. Altitude varies between 1420 and 1760 m (Mucina & Rutherford, 2006).

4.3.3 Climate

Soweto is situated south-west of Johannesburg in a warm temperate region of South Africa. It experiences summer rainfall and high temperatures, offset by cold, dry winters where the occurrence of frost is common. The mean monthly temperature in at this study site is 16.8°C, with a mean maximum of 22.6°C and a mean minimum of 10.8°C. The mean winter temperature in the study area is 13.8°C and the mean summer temperature is 25.6°C. Mean annual precipitation peaks at 662 mm, although extended dry periods have been experienced in the last few years (Mucina & Rutherford, 2006).

4.3.4 Historical average rainfall and temperature

Johannesburg experienced higher temperatures during the study, on average, than historical figures (Figure 4.5). Periodic rainfall events and low overall rainfall experienced led to a shift in growth season applicability from October to February (2002 – 2012), which led to shorter plant growth timeframes available for establishment prior to winter drought and cold temperatures (www.worldweatheronline.com – date of access: 12 June 2016). These factors influenced not only the agricultural sector but the rehabilitation sector through smaller windows of opportunity for successful vegetation establishment on mine TSFs.

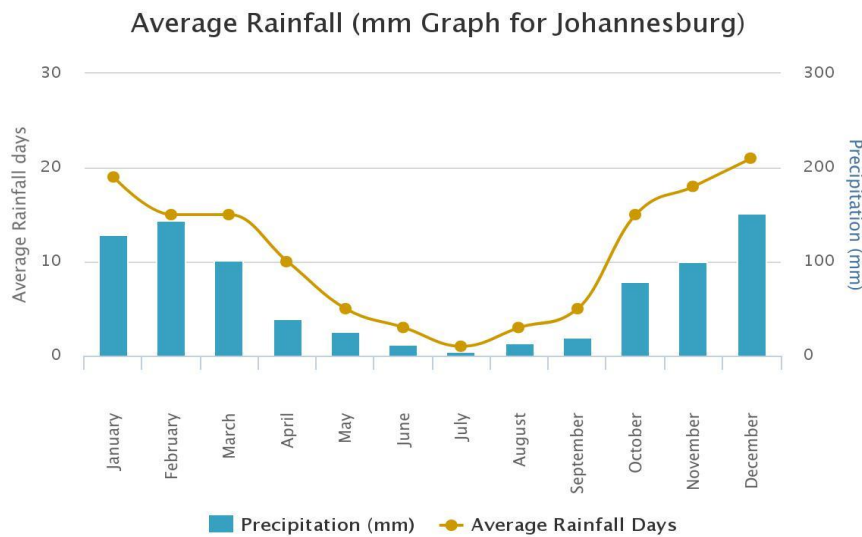
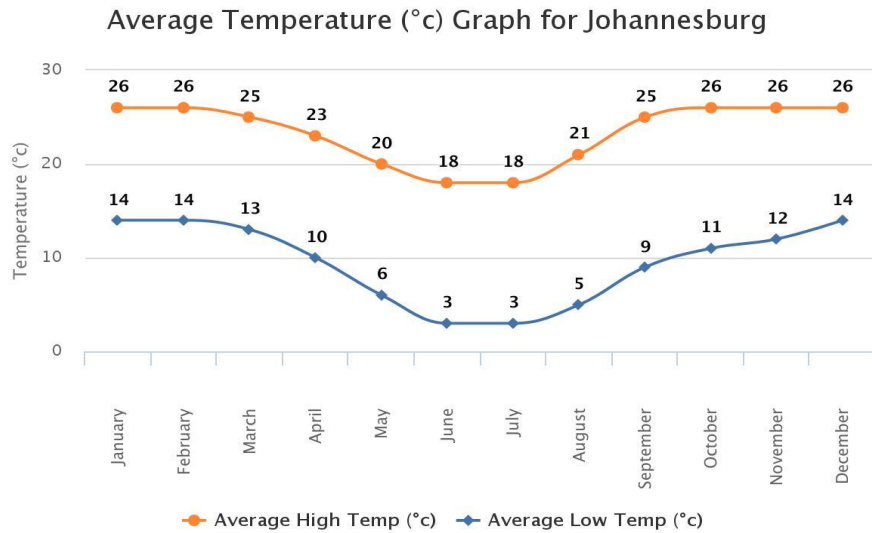


Figure 4.5: Johannesburg historical rainfall and temperature data (10 year average) (www.worldweatheronline.com, date of access 12 June 2016).

4.3.5 General description of geology and soil (Crown and Rooikraal TSFs).

The study sites form part of the Witwatersrand basin that was formed between 3074 and 2714 million years (Ma) ago over a period of 360 million years. Metamorphic fluid circulation led to the basin undergoing three stages of remobilisation from 2500 to 2000 Ma, the most recent of which occurred in 2000 Ma, leading to a widespread distribution of gold and the formation of various secondary sulphides (Robb & Meyer, 1995). As a result of this redistribution of gold, an amount of about 45000 tonnes of gold has been available for mining over a period of 100 years, stretching from the

1890s to the 1990s. By 1990, this was more than 35% of all the gold mined in the history of mankind (Handley, 1990). After the formation of the basement granite, sedimentary basins with associated volcanic rocks began to develop. The most important of these basins contains a sequence of quartzite, conglomerates and shale and is known as the Witwatersrand Super Group (Viljoen & Reimold, 1999). Owing to their age (approximately 3000 million years), these sediments have been largely covered by younger rock sequences and generally outcrop on the surface only where they have been exhumed by uplift and erosion. Gold in the sedimentary rocks of the Witwatersrand basin (Figure 4.6) occurs as minute grains in narrow pebble bands or conglomerate layers called reefs (Viljoen & Reimold, 1999).

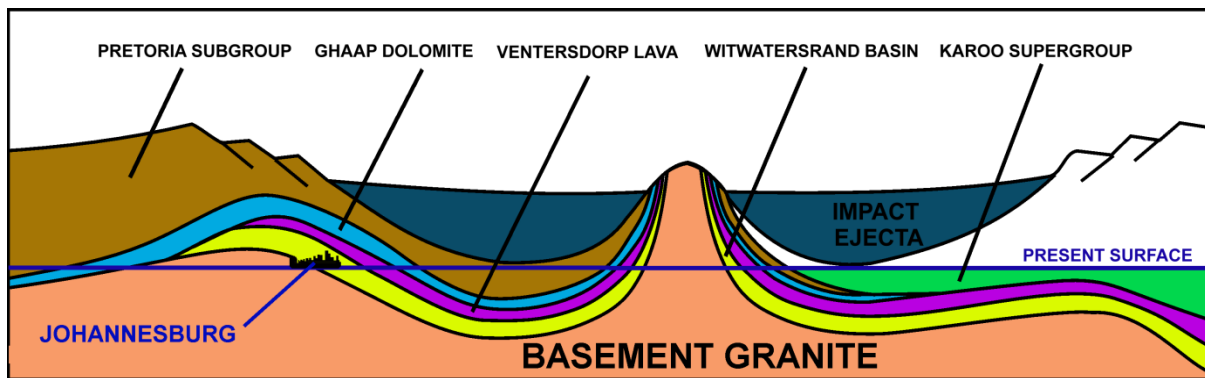


Figure 4.6: Graphic illustration of the basins surrounding the Johannesburg.

These extensive gold-bearing layers are unique and have made South African gold mines world-famous. South African mines have yielded approximately 45000 tonnes of gold since mining commenced in 1886, making the Witwatersrand by far the world's greatest gold field. Some of the gold reefs are now being mined at depths approaching 4000 metres and the technological know-how needed to achieve this has made South Africa a world leader in deep-level mining (Viljoen & Reimold, 1999). Due to the financial and economic advantages of gold mining, the industry has extensively operated wherever gold ore has been identified in the country.

However, the environmental impact can be severe: Acid rock drainage (ARD) is encountered during the gold mining process and waste production of different minerals such as gold, nickel and copper occurs. ARD is the result of iron sulphide aggregate material being exposed to oxygen and water, which is also increased by

the amount of available sulphides due to the mining process (Akcil & Koldas, 2005). According to Van Deventer and Schoeman (2004), ARD occurs when water moves through oxidised pyrites in mine workings or TSFs. This chemical interaction causes very low water pH levels, high salinity and contamination with heavy metals such as iron, manganese and lead.

4.3.6 Trial layout and plot description (Crown and Rooikraal TSFs)

Figure 4.6 and Table 4.3 show the available sites for field trials on Crown gold TSF flat plots comprised an area of 600 m² (six plots of 10 x 10 m). On the slopes, trials consisted of 192 m² (six plots of 8 x 4 m).

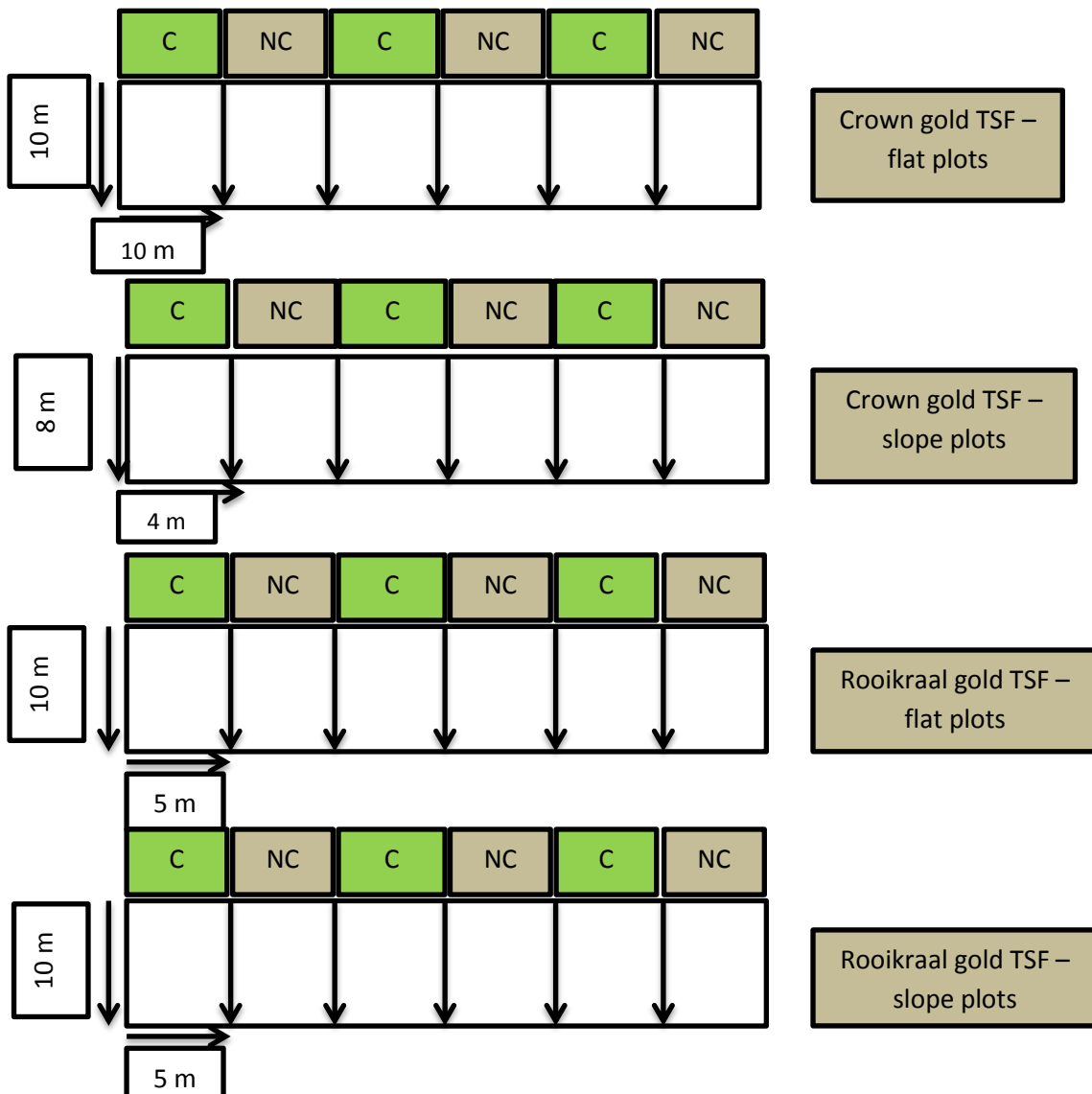


Figure 4.7: Field trial layout for Crown and Rooikraal gold mine tailings storage facilities (TSFs) C: coated seed; NC: non-coated seed.

Table 4.3: Description of field trial plots at Crown and Rooikraal gold mine tailings storage facilities (TSFs). C: coated seed; NC: non-coated seed.

Slope factor/trial location	Plot size and repetition	Soil type	GPS coordinates	Seed types
Crown gold TSF – flat plots 2015 and 2016.	10 x 10 m – Three plot repetitions each of C and NC.	Acidic, fine white, sandy.	26°14'37.3"S; 27°58'03.4"E	C and NC – <i>Cynodon dactylon</i> , <i>Eragrostis curvula</i> , <i>Medicago sativa</i> , <i>Sorghum</i> sp.
Crown gold TSF – slope plots 2015 and 2016.	8 x 4m – Three plot repetitions each of C and NC	Acidic, fine white, sandy.	26°14'18.1"S; 27°57'54.1"E	C and NC – <i>C. dactylon</i> , <i>E. curvula</i> , <i>E. tef</i> , <i>M. sativa</i>
Rooikraal gold TSF – flat plots 2015 and 2016.	10 x 5 m – Three plot repetitions each of C and NC.	Acidic, fine white, sandy.	26°21'20.3"S; 28°17'23.3"E	C and NC – <i>C. dactylon</i> , <i>E. curvula</i> , <i>M. sativa</i> , <i>Sorghum</i> sp.
Rooikraal gold TSF – slope plots 2015 and 2016.	10 x 5 m – Three plot repetitions each of C and NC.	Acidic, fine white, sandy.	26°21'19.9"S; 28°17'22.8"E	C and NC – <i>C. dactylon</i> , <i>E. curvula</i> , <i>M. sativa</i> , <i>Sorghum</i> sp.

4.4 Nigel (Rooikraal TSF)

4.4.1 Trial location

The Rooikraal gold TSF is situated in the Gauteng province within the Grassland biome. This biome is diverse in species composition and consists of predominantly C4 grass species, geophytes and some shrubs and trees (Mucina & Rutherford, 2006).

The study site is situated near Nigel in the Gauteng province (Figure 4.1).

Rehabilitation at Rooikraal TSF has been completed by Agreenco Environmental Projects and signed off. The Rooikraal TSF is located next to the ERGO Mining Ltd

TSF, directly opposite Reiger Park near Nigel (Figure 4.1). Site operation commenced during the 1980s and finished during the 1990s, after which it was rehabilitated and closed. The top surface area is approximately 97 ha and the base 140 ha.

4.4.2 Vegetation

As with the Mooifontein TSF, the Rooikraal TSF also falls within the Grassland biome (Mucina & Rutherford, 2006). It is characterised by slightly undulating plains and hills (altitude, 1480–1680 m) and consists mainly of short, dense grassland with species such as *Themeda triandra*, *Heteropogon contortus*, *Elionurus muticus* and a number of *Eragrostis* species. The area is greatly impacted by industrialisation, specifically mining and commercial farming.

4.4.3 Climate

Rooikraal TSF is situated on the outskirts of Nigel, Gauteng, and experiences warm temperate conditions that are similar to those of Johannesburg. Summer rainfall (630–720 mm per season) is offset by cold, dry winter periods. Temperature variation indicates the transition between cool temperate and warm climate regions.

The area receives its lowest rainfall (0 mm) in June and its highest (115 mm) in January. The monthly distribution of average daily maximum temperatures shows that the average midday temperatures for Nigel range from 16.7°C in June to 26°C in January. The region is the coldest during July, when the temperature drops to 0.1°C on average during the night.

4.4.4 Historical average rainfall and temperature

Historical data show that the Nigel (Rooikraal TSF) area on average receives high rainfall over an extended period (Figure 4.6), which indicates the tendency for high agricultural yield in the area. When compared to climatic data over the trial period, fewer rainfall days were encountered with higher average temperatures, followed by short periods of high-intensity rainfall, which compounds erosion probability.

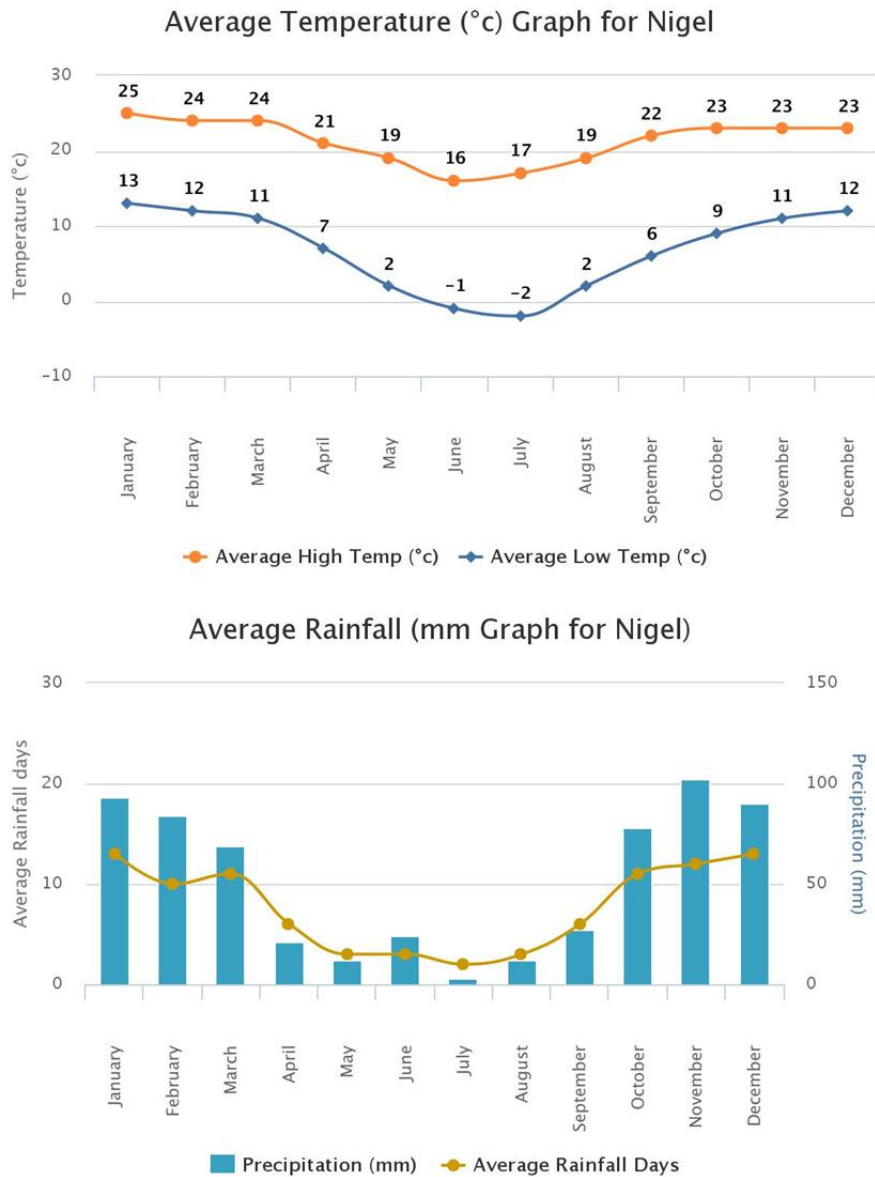


Figure 4.8: Nigel historical rainfall and temperature data (10-year average) (www.worldweatheronline.com, date of access 12 June 2016).

4.4.5 Geology and soil

Please refer to section 4.3.5 and 4.3.6 of this chapter including Figure 4.7 and Table 4.3 for reference to Rooikraal TSF geology, soil, plot description and layout.

4.5 Study site rehabilitation procedures

Agreenco Environmental Projects compiled rehabilitation proposals that include rehabilitation measures, timeframes and budgets for rehabilitation carried out at a specific site. These proposals are linked directly with the environmental management plan submitted by a specific mine during the environmental impact assessment phase, which states the quality of rehabilitation required for a mine to receive closure as required by the Department of Mineral Resources and Department of Environmental Affairs.

4.5.1 Location and availability of workforce and machinery

The seedbeds were ripped to a depth of 30 cm by hand to allow effective ameliorant infiltration and reaction. This required time and a willing workforce in each instance and this stage took approximately three days to complete. At Rooikraal, rehabilitation by Agreenco Environmental Projects was complete and thus a very limited workforce (two workers) were available to assist. Machinery was also required to transport ameliorants to each trial site.

4.5.2 Available ameliorants

Due to the acidic nature of the gold mine TSF trial sites in this study, the following procedures were followed to adjust/amend the pH levels to allow plant growth and establishment as per Agreenco Environmental Projects specifications. Lime is commonly used to increase the low pH levels to enable plant seed to germinate and grow. The procedure to prepare the plots for this study at the gold mine TSFs is described in the following sections.

All ameliorants used were determined according to Agreenco Environmental Projects rehabilitation specifications. Lime was added by hand and left in situ to stabilise pH levels. Fertiliser (3:2:3 and superphosphate) and a well-decomposed mushroom compost was added prior to seeding, after which seed mix bags (*Cynodon dactylon*, *Eragrostis curvula*, *E. tef*, *Medicago sativa* and *Sorghum* sp.) were sown by hand (broadcasting method) on individual plots.

The following ameliorants were added to the trials at Crown and Rooikraal TSFs:

Slope trials:

Dolomitic lime (120 t/ha) – 2304 kg (12 kg/m²) lime for slope trials at Crown (192 m²) and 3600 kg at Rooikraal (300 m²).

Well-decomposed mushroom compost (60t/ha) – 1152 kg at Crown, 1800 kg at Rooikraal (300 m²) and 864 kg at Paardekraal (144 m²).

4:3:4 (34) fertiliser (400 kg/ha) – 8 kg at Crown, 12 kg at Rooikraal and 6 kg at Paardekraal.

Superphosphate (600 kg/ha) – 11.5 kg at Crown, 18kg at Rooikraal and 8.6 kg at Paardekraal.

1:0:1 (32) fertiliser (200 kg/ha) – 4 kg at Crown, 6 kg at Rooikraal and 3 kg at Paardekraal.

Flat trials:

Dolomitic lime (85 t/ha) – 5100 kg at Crown and 2550 kg at Rooikraal.

Well-decomposed mushroom compost (40 t/ha) – 2400 kg at Crown and 1200 kg at Rooikraal.

4:3:4 (34) fertiliser (400 kg/ha) – 24 kg at Crown and 12 kg at Rooikraal.

Superphosphate (600 kg/ha) – 36 kg at Crown and 18 kg at Rooikraal.

1:0:1 (32) fertiliser (200kg/ha) – 12 kg at Crown and 6 kg at Rooikraal.

Ameliorants were spread by hand over the trial plots and worked into the tailings material with pitch forks. Lime was used first and left for three of weeks to allow adequate infiltration and reaction. Thereafter the seed was hand sown, compost was added, covered by scraping of the tailings material and left to germinate.

Mulch was then used to cover each plot with approximately 60% cover to enable improved water retention, erosion control and protection from wind and over-exposure to sunlight. All plots were covered with mulch in 2015 and 2016 except for

the top flat plots at Crown Gold mine, which were left without mulch in 2015 to determine the importance/necessity of mulch for the germination, growth and establishment of the grass species (coated and/or non-coated seed) at the gold TSFs. The top flat plots were covered in 2016 to show the difference between the 2014/2015 and 2015/2016 growing seasons.

4.5.3 Topography

One of the major influences on the successful rehabilitation of mine TSFs is the slope angle. Due to the size/area required for the storage of such massive amounts of tailings material, the slope angle is commonly increased to as much as 35° whereas the proposed optimal angle for rehabilitation success should not exceed 14°. Due to the increased angle, environmental factors are compounded to further complicate the successful establishment of vegetation due to wind speed, erosion and water infiltration capability, as discussed in previous chapters (Mohr-Swart & Tanner, 2007). The slope factors at Crown and Rooikraal were as follows: Crown slope – average of 25.2°; Crown flat – average of 1.25°; Rooikraal slope – average of 24.5°; and Rooikraal flat – average of 1.18°.

4.5.4 Trials on slope areas – Mooifontein and Rooikraal gold tailings storage facilities

Slope areas are susceptible to erosion and high wind speed, which damages seedlings during early growth stages. The chemical composition of gold TSF slopes also differ although the pH levels remains relatively similar to the top flat plots. The fertiliser used during soil amelioration in this study was also proposed by current mine TSF rehabilitation specialists to ensure healthy growth and establishment of vegetation with application before seeding. Common descriptions on labels for fertilisers can be confusing; the values listed below only reflect the percentage composition of each nutrient relative to each other and the weight of the fertiliser used. For example, 4:3:4 used in this case refers to 4% nitrogen, 3% phosphate and 4% potassium. For a 50 kg bag, the ratios would therefore indicate that 8 kg consists of nitrogen, 6 kg of phosphate and 8 kg of potassium – 22 kg in total – while the rest

of the weight consists of trace elements required for plant growth or health as well as additional elements that assists with fertiliser absorption and breakdown in soil.

The grass seed sown (broadcast) by hand on slope areas differed from normal agricultural amounts. The seed mixture was as follows:

- 4 kg/ha *C. dactylon* (couch grass)
- 4 kg/ha *E. curvula* (weeping love grass)
- 1 kg/ha *E. tef* (teff grass)
- 3 kg/ha *M. sativa* (lucerne)
- 3 kg/ha *Sorghum* sp. (forage sorghum)

Top flat plots are susceptible to high temperatures and little shade. Compaction is also common, which prohibits vegetation from forming adequate root systems and limits water availability to the plant (Van Deventer & Schoeman, 2004). When the plots are ripped by hand (pitchforks), as in this study, it becomes difficult to rip deeper than 300 mm. The mixture of grass seed sown on top flat areas was as follows:

- 4 kg/ha *C. dactylon*
- 4 kg/ha *E. curvula*
- 3 kg/ha *M. sativa*
- 3 kg/ha *Sorghum* sp.

4.6 Study site soil sampling

Soil sampling took place in 2015 prior to soil amelioration and the samples were analysed by Eco Analytica Laboratories in Potchefstroom⁵. Composite samples of each plot were taken to a depth of 30 cm. The pH, electrical conductivity (EC), and the percentage of nitrogen, phosphate, potassium, calcium and magnesium contents of the TSFs were determined. The pH levels and EC of each sample from every plot were analysed over a six-month period to establish fluctuations and stabilisation of pH, specifically due to the addition of lime, fertilisers and the impact on plant growth activity.

⁵ Thabo Mbeki Drive (R501), Potchefstroom, 2531

The soil amelioration of platinum TSFs was different to that of gold TSFs. The addition of lime was omitted in the amelioration of the platinum TSF mainly due to the high pH levels encountered at these sites. pH levels of 7–9 were measured and though it may seem preferable, such high levels may lead to the non-availability of some plant nutrients as shown in Figure 1.2 (Chapter 1). High pH levels also lead to an increase in the soil salinity, which may inhibit the growth and establishment of certain plant species (Spitz & Trudinger, 2009).

Another factor that should be considered during rehabilitation and soil amelioration efforts is plant-available nutrients. Nutrients in the soil allow plant establishment and growth through the production of amino acids and protein synthesis. Primary nutrients for plant health are nitrogen, phosphate and potassium, supported by secondary nutrients such as calcium, magnesium and sulphur (MVSA, 2007).

5. Trial site methodology

The study consisted of field trials undertaken during the 2014/2015 and 2015/2016 growth seasons. The following outline describes the approach to establish the scientific baseline for this study:

1. A review of previous greenhouse and laboratory trials was undertaken (2015) to select the most suitable species for field trials in dryland TSF conditions.
2. Selection of field trials sites were completed with the assistance of the project sponsors and partners listed below (Agreenco Environmental Projects⁶ and AGT Foods Africa (Pty) Ltd⁷).
3. Preparation of the field trial sites were undertaken (soil preparation, amelioration, fertilisation and seed placement); trials on flat and sloped angles were prepared in 2015 and 2016.
4. Surveys were conducted over the two-year study period to establish and compare germination, growth and survival of the selected plant species and the influence of

⁶Agreenco Environmental Projects; Holdings 467, Vyfhoek, Potchefstroom, 2531; Tel: +27 18 285 7317

⁷AGT Foods Africa (Pty) Ltd; 8 Jacobs St., Chamdor, Krugersdorp, 1739; Tel: +27 11 762 5261

soil nutrient factors on these species in terms of coated and non-coated seed sown on slopes and flat plots on gold and platinum TSFs.

The species chosen for the study, as mentioned earlier, were *C. dactylon*, *E. curvula*, *E. tef*, *M. sativa* and forage sorghum (*Sorghum* sp.) and were used in 2015 and 2016 for comparative results. Coated and non-coated seed were used for each species except for *E. tef* (only non-coated seed were available in 2016). *Eragrostis tef* was used in place of *Sorghum* sp. on sloped trials at Crown gold TSF due to the mine rehabilitation specification requirements. The same seed batches were used for coated and non-coated seed throughout the study period and were laboratory proven to be 80% viable (<http://www.advanceseed.com>).

All the trials for this study were undertaken under dryland conditions, except for the slope plots at the Crown gold TSF. Because of the rehabilitation specification requirements, the slopes were already under irrigation and the trial was adapted to suit these conditions and included as a control to indicate the influence of irrigation on vegetation establishment and successful rehabilitation. Comparisons for the study were based on the impacts of dryland conditions commonly encountered at gold and platinum mine TSFs, the influence on main growth factor requirements for successful vegetation establishment and the critical amelioration focus areas, namely soil quality, slope factor and water and nutrient availability.

For the purpose of this study, the selected sites were monitored and surveyed over time to establish germination, growth, establishment and survival of the seed sown. The surveys were conducted as follows:

1. Initial survey during the rainy season (germination).
2. After the winter (survival).
3. Repeated the following year to establish survival and second-generation seed viability of the trial site vegetation. A short description of the species used in the trials is given below:

***Eragrostis curvula* – weeping love grass**

According to Van Oudtshoorn (2012), *E. curvula* is a strong, thick perennial grass species commonly found in large parts of South Africa, specifically in the eastern and

south-eastern provinces such as Limpopo, Mpumalanga, North-West, Gauteng, KwaZulu-Natal and Eastern Cape. It is usually found in well-drained but disturbed soils such as old agricultural fields and road reserves. The species is commonly associated with planted grazing in the cold Highveld region of South Africa. It has a relatively low palatability and is therefore not seen as the best natural grazing but is rather combined with other species such as *E. tef*, *Cynodon dactylon*, *Digitaria eriantha* and *Cenchrus ciliaris* to form a stable grazing or baling pasture for winter feed. Flowering occurs from August to June. The analysis of the seed was completed by AGT Foods Africa prior to the undertaking of the field trials. The seed cultivar provided by AGT Foods Africa⁸ was *Eragrostis* Ermelo; a full analysis report is provided in Annexure A.

***Cynodon dactylon* – couch grass**

Cynodon dactylon is a perennial creeping grass species found in most of the world's warm temperate regions. It spreads through rhizomes and stolons to form a carpet-like cover. It is regarded similar to *E. curvula* because it is found naturally in disturbed soils, although more so in sandy soils. It is also commonly used as planted grazing due to its high palatability, is considered a solution to soil erosion because of its creeping nature and soil-holding capabilities and is favoured in lawns because of its drought-resistant nature. Flowering occurs from September to May (Van Oudtshoorn, 2012). The seed analysis was completed by AGT Foods Africa prior to the undertaking of field trials. The seed provided was *Cynodon*; a full analysis report is provided in Annexure A.

***Medicago sativa* – lucerne**

Medicago sativa is also known as alfalfa, which means “best fodder” and is a perennial flowering plant. Lucerne yields large volumes of high-quality hay that is rich in protein and is therefore seen as a viable commercial production plant choice. This species belongs to the legume family, which fixes nitrogen in soil through symbiosis with bacteria, such as rhizobia, making it available for plant growth. In South Africa, lucerne is grown under irrigation and as a dry-land crop. It prefers well-drained soil of about 1.2 m deep because of its deep penetrating root system. It resembles clover

⁸ AGT Foods Africa (Pty) Ltd
8 Jacobs street, Chamdor, Krugersdorp, South Africa
Phone: +27 011 762 5261/2

and has clusters of small purple flowers (Van Oudtshoorn, 2012). The analysis of the seed was completed by AGT Foods Africa prior to the undertaking of field trials. The seed provided was Lucerne Supercuf; a full analysis report is provided in Annexure A.

***Eragrostis tef* – teff**

Eragrostis tef is an annual, tufted grass commonly found in disturbed soil and used widely as planted grazing, for commercially bales as winter feed and as a solution to soil erosion because of its ability to establish quickly in most soil types. It is a popular feed for horses, but also used in Ethiopia for the production of a local bread called *injera*. The species is used widely for rehabilitation in a mix with *E. curvula* and *C. dactylon* because of its swift establishment. Originally from the north-eastern parts of Africa, the species is now commonly encountered in central South Africa (Van Oudtshoorn, 2012). The analysis of the seed was completed by AGT Foods Africa prior to the undertaking of field trials. The seed provided was Tef SA Brown; a full analysis report is provided in Annexure A.

***Sorghum* sp. – forage sorghum**

Forage sorghum is a widely suited annual summer grass. It is commonly used and planted commercially as fodder, with high production value in fertile soils and the added benefit of being drought resistant (with survival and production under rainfall as low as 350 mm annually). The most common types of commercially available sorghum is sweet sorghum and sweet sorghum-Sudan grass variations (AGT Foods Africa Online, 2016). These cultivars differ in terms of flowering times, which influence the length of their growth season and productivity but allows suitability in different climates. Prussic acid can be produced by *Sorghum* species when under stress and is seen as one of the major negative effects in the planting of sorghum (Van Oudtshoorn, 2012). The viability analysis of the seed was completed by AGT Foods Africa prior to the undertaking of field trials. The seed provided was Forage Sorghum SSG1000 and Supergraze; a full analysis report is provided in Annexure A.

The study timeline is indicated in Figure 4.9 for reference.

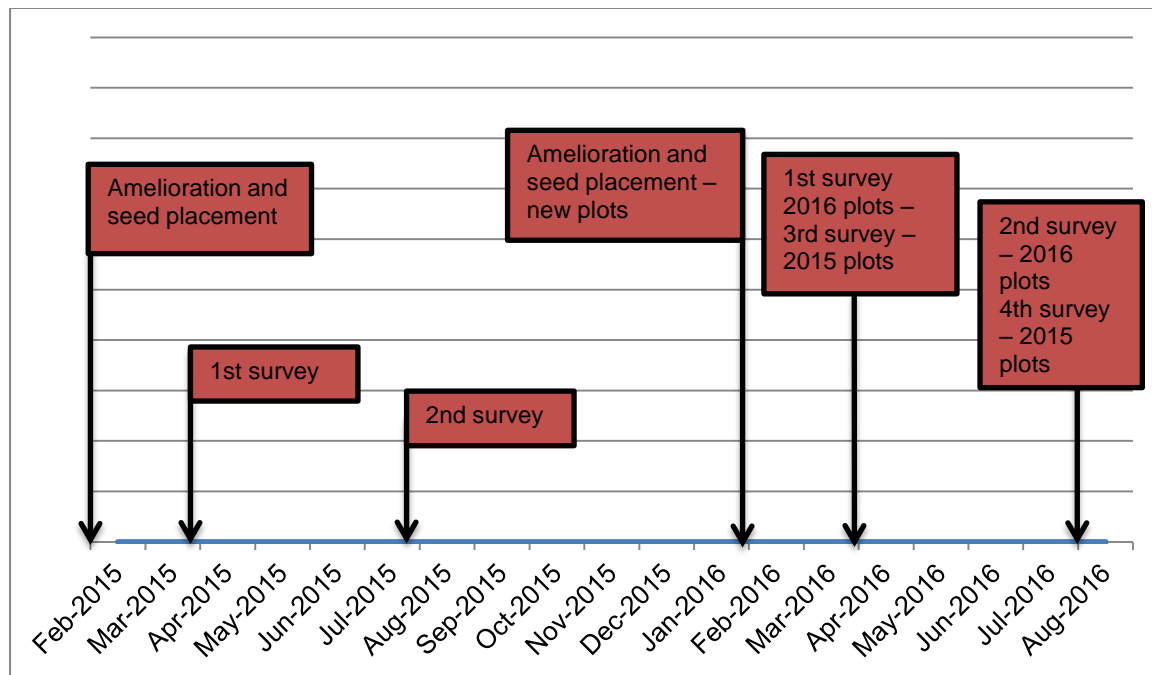


Figure 4.9: Timeline of study and sampling periods from February 2015 to August 2016 as well as periods of rehabilitation and amelioration activities.

Data from the South African Weather Service⁹ were used to establish rainfall and temperature variance and compare vegetation survey data to determine the influence of these climatic factors on the study outcomes over two growth seasons (2014/2015 and 2015/2016). Average temperatures were used to illustrate the impact of soil temperature on vegetation rehabilitation on gold and platinum mine TSFs.

6. Study sites – rainfall and temperature

For the purpose of this study, rainfall data were gathered to illustrate the monthly precipitation experienced during the two growth seasons within which the field trials were undertaken. The study site locations were grouped to illustrate comparisons (Figure 4.10). Low rainfall was experienced in South Africa during the study trials – when comparing Rustenburg’s rainfall over December 2014 to May 2015 with historical rainfall data the impact of drought on the establishment of vegetation in this area is apparent.

⁹442 Rigel Avenue South, Erasmusrand, 0181, Pretoria; Tel: +27 12 367 6000

Rainfall data used for Crown gold TSF were gathered by the Johannesburg Botanical Garden; for Rooikraal gold TSF data were gathered by the Nigel Fire Department and for Paardekraal platinum TSF data were gathered by the South African Weather Service in Rustenburg. Rain meters could not be kept for extended periods on the trial sites for fear of theft, thus the closest official rain measurements to each trial were used.

During December 2009 to May 2010, precipitation in Rustenburg reached an average of 610.8 mm. During December 2014 to May 2015, Rustenburg received 160.2 mm – only 26% of the normal average rainfall for this area. Low rainfall, combined with high average temperatures encountered in this area, impacted seed viability in dark platinum TSF soils negatively. The graphs below (Figures 4.10 -14) indicate the actual monthly rainfall (mm) and temperature (C°) experienced over the trial period (October 2014–May 2016) and historical averages for the same locations (2002–2012).

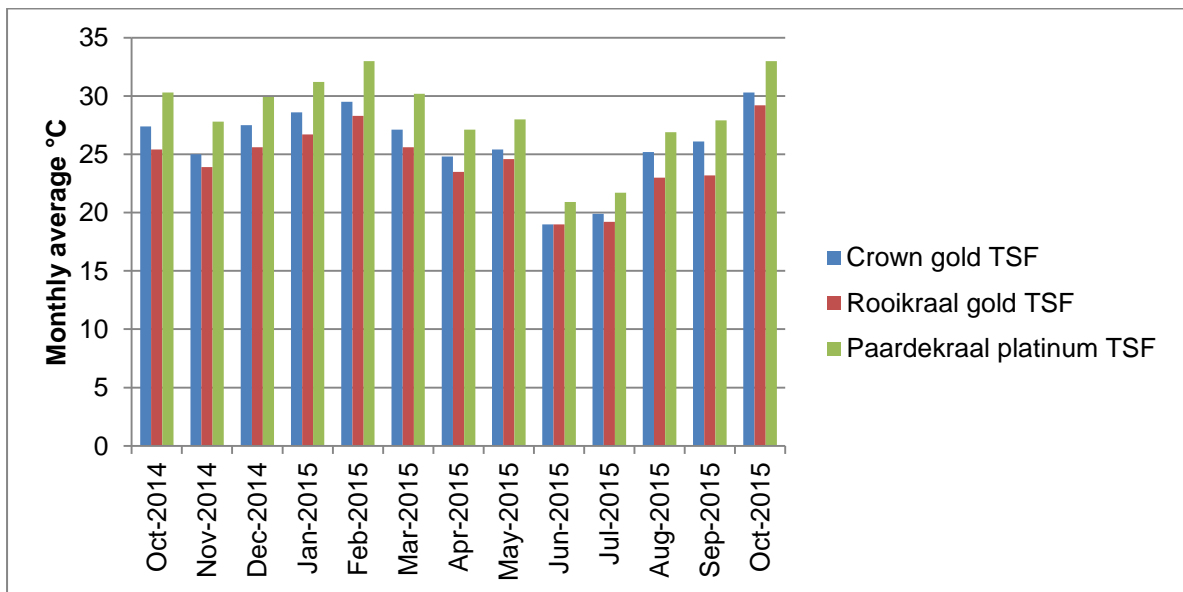


Figure 4.10: Monthly average temperatures (°C) for the three field trial locations from October 2014 to October 2015. TSF: tailings storage facility.

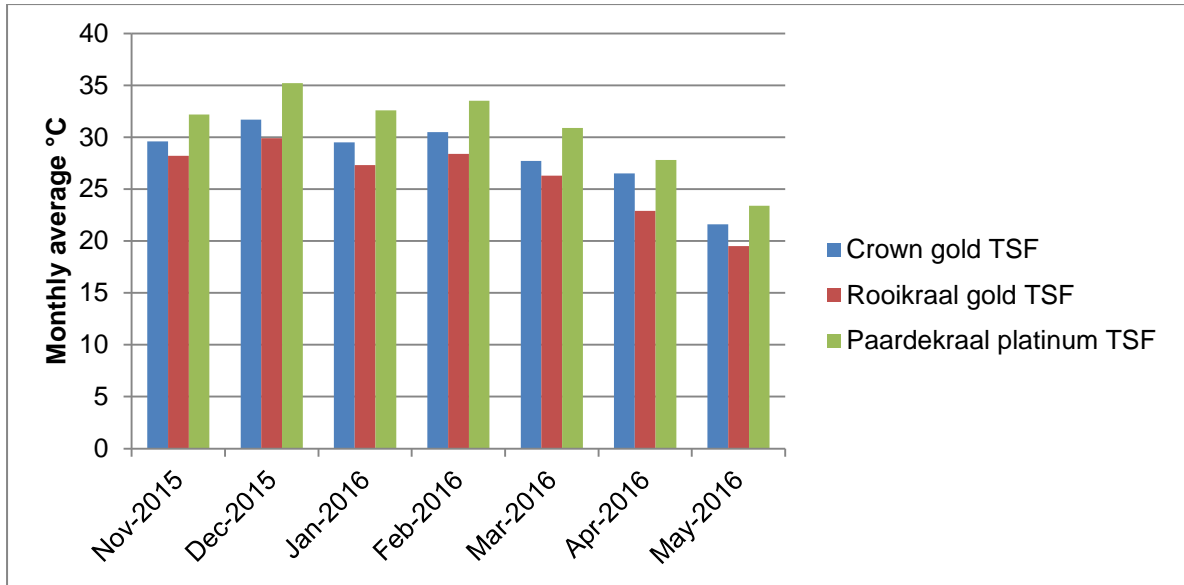


Figure 4.11: Monthly average temperatures (°C) for the three field trial locations from November 2015 to May 2016. TSF: tailings storage facility.

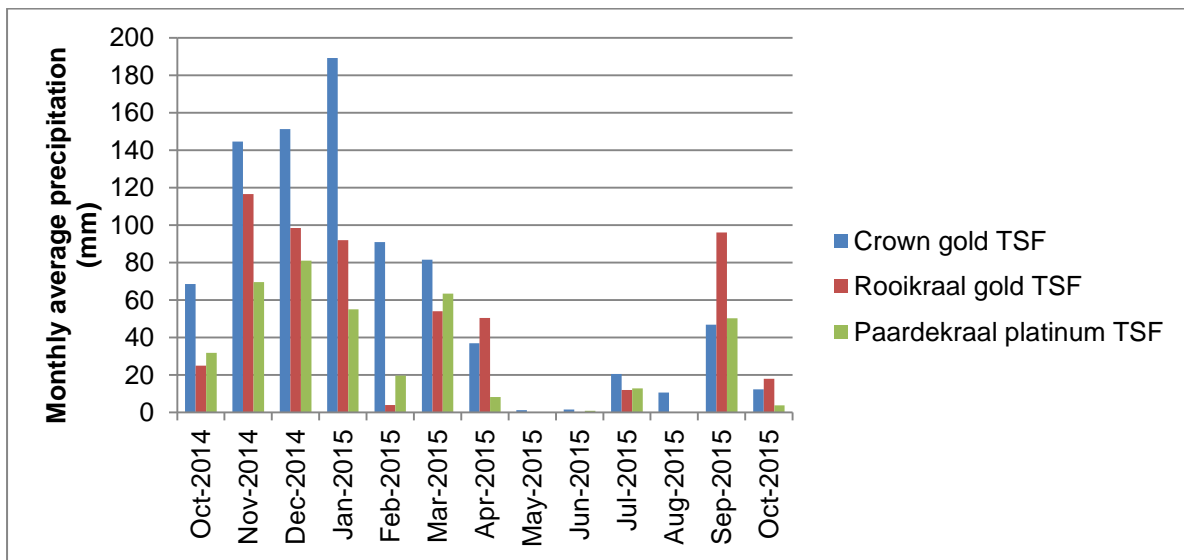


Figure 4.12: Monthly average precipitation (mm) for the three field trial locations from October 2014 to October 2015. TSF: tailings storage facility.

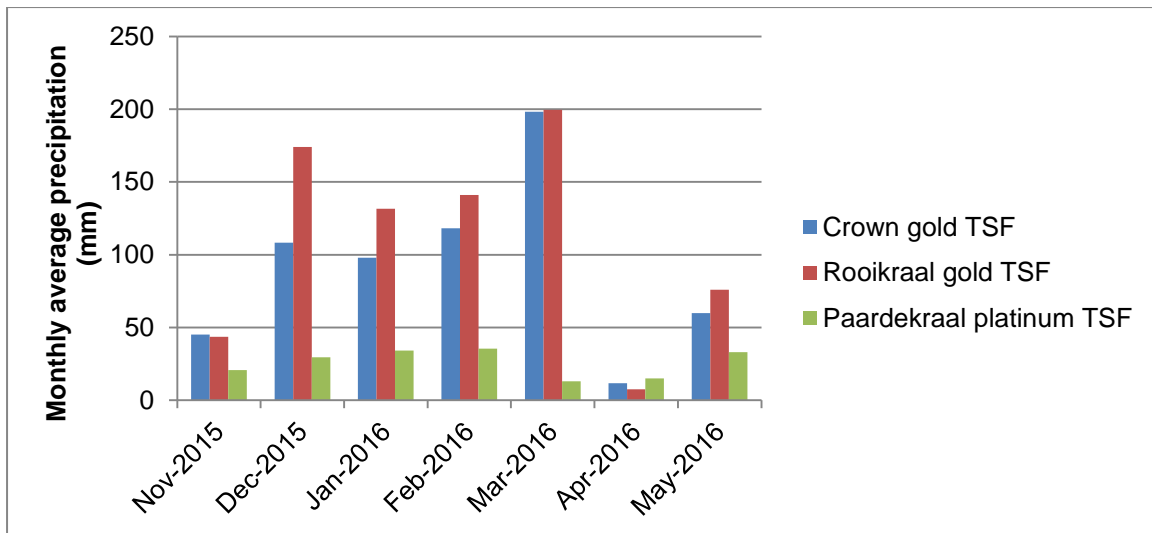


Figure 4.13: Monthly average precipitation (mm) for the three field trial locations from November 2015 to May 2016. TSF: tailings storage facility.

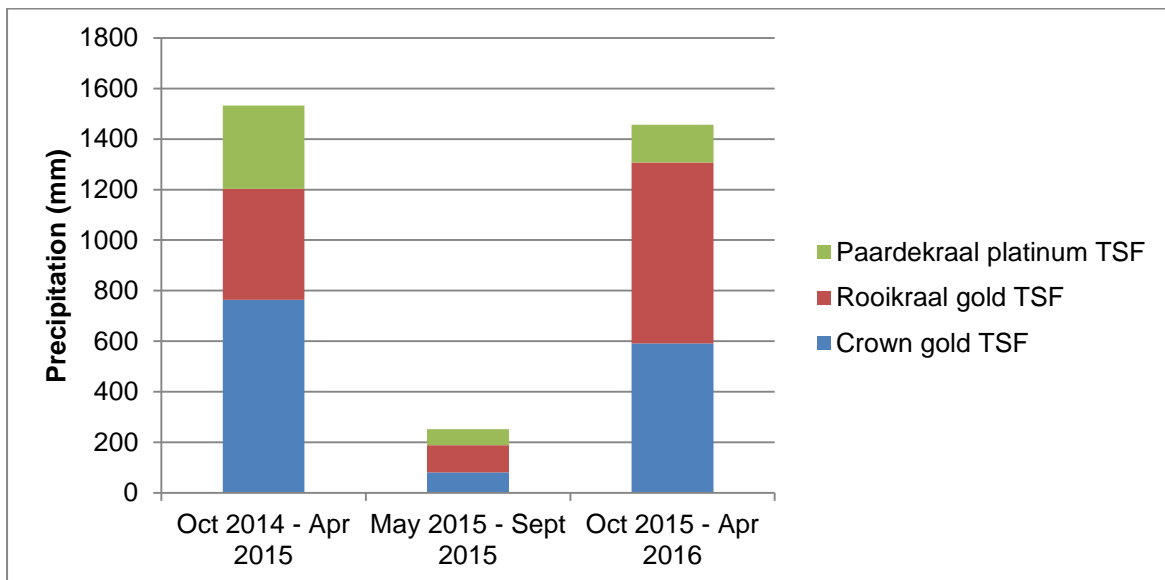


Figure 4.14: Comparison of the total precipitation (mm) at each trial location. TSF: tailings storage facility.

As indicated by the data above, Rustenburg received the lowest average rainfall and the highest average temperatures during the trial period. These factors combined to influence the germination and survival of the species planted at Paardekraal TSF. Extended drought prohibited seed germination and survival through the inability to develop sufficiently into strong adult plants and is supported by (Radic *et al.*, 2007). The species that germinated after short bouts of rain were left exposed and unable to withstand the environmental pressure exerted by windblown platinum TSF

particles, heat exposure and lack of sufficient nutrient production capabilities of the soil as well as low absorption due to availability of nutrients.

7 Experimental design and layout of field trials

The field trials were established on slope and flat surfaces to simulate current challenges in gold and platinum mine TSF rehabilitation (Figure 4.15). Slopes of up to 30% are common at some mine TSFs in South Africa, exponentially increasing the challenge to rehabilitate successfully. Ideal rehabilitation slopes should not exceed 14% to minimise erosion and wind damage on vegetation while ensuring structural integrity (Mohr-Swart & Tanner, 2007). As shown below (Figure 4.15) – the trials were separated into similar size plots/blocks with equal repetitions between coated and non-coated seed plots. Three repetitions each were attempted to evaluate the performance of each species and the effect of coating vs. non-coating efficiency. The figure below (Figure 4.15) shows the plot sizes and layouts on gold and platinum mine TSF sites. Plots planted with coated seed are illustrated with a green “C”, whereas plots sowed with non-coated seed are indicated by a brown “NC”.

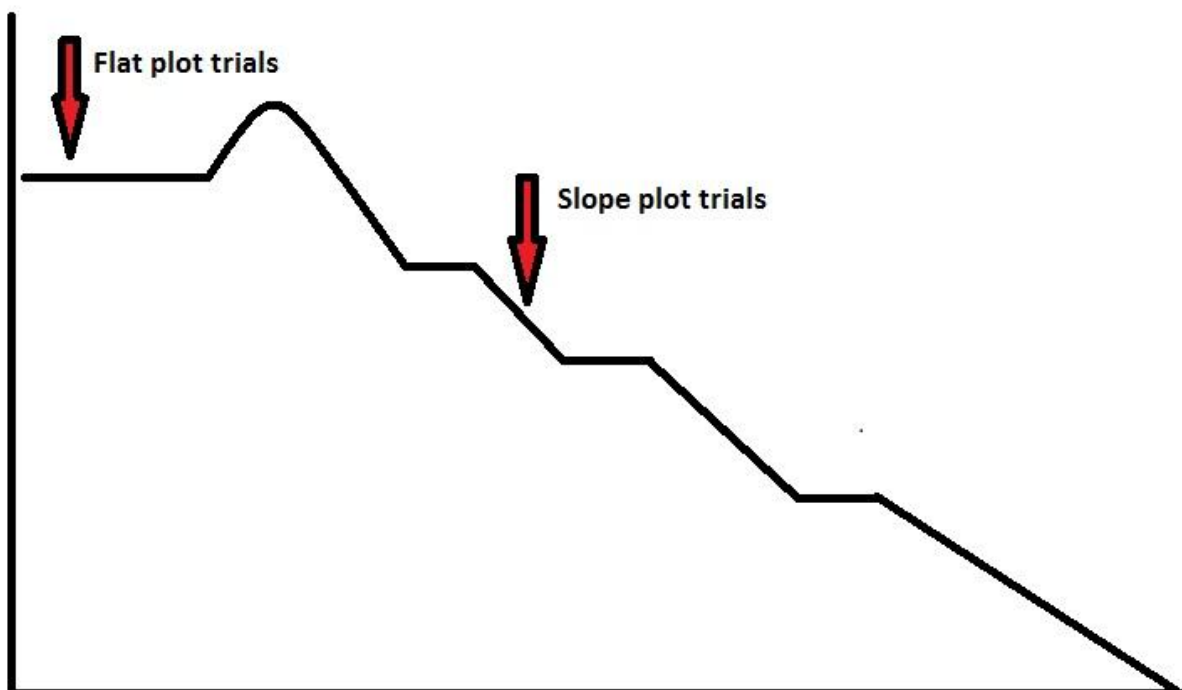


Figure 4.15: Mine tailings storage facility side view. Field trials were established on slope and flat surfaces.

8. Monitoring of field trials

Vegetation surveys were conducted during the study to establish significant differences between germination, growth, establishment and re-growth of coated and non-coated seed species. These surveys included subjectively placing a number of quadrants (50x 50 cm) within each plot to evaluate the number of germinated plants per species within the quadrant (Figure 4.16). This enabled the determination of the density of each species per m², which would enable quantification of the seed coating effect or degree of success for a rehabilitation effort. The frequency of the species was determined through the use of a transect across each individual plot at pre-determined and spaced intervals. This ensured that repetition was comparable (every metre) and the point-toe method was used, adding to the density data to show which species established best and were most frequently encountered within each plot area. In turn, this provided data whereby the uniformity of the established community and distribution of each species could be determined.



Figure 4.16. Density and frequency surveys through subjective placement of transects and quadrants in each plot (Photo: H Taute 2016).

Each survey was repeated to obtain sufficient data from each plot, which could be extrapolated to a larger surface area to measure targets required for rehabilitation success as shown and in Figures 4.17 and 4.18.

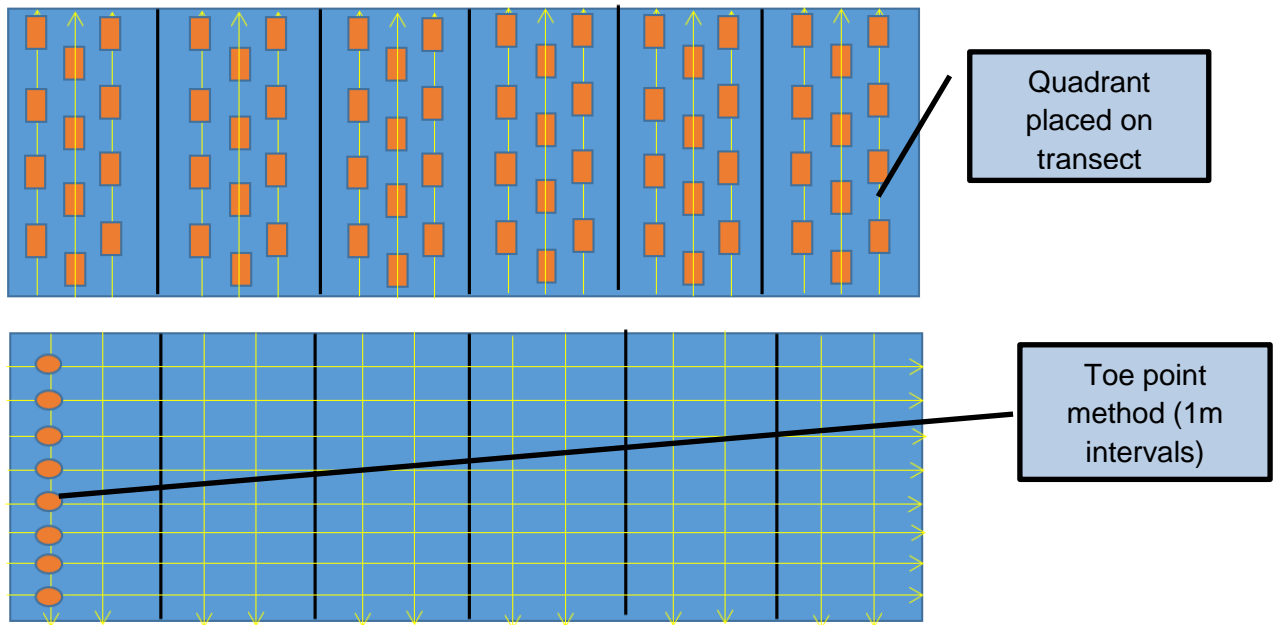


Figure 4.17: Slope plots survey method at all trials.

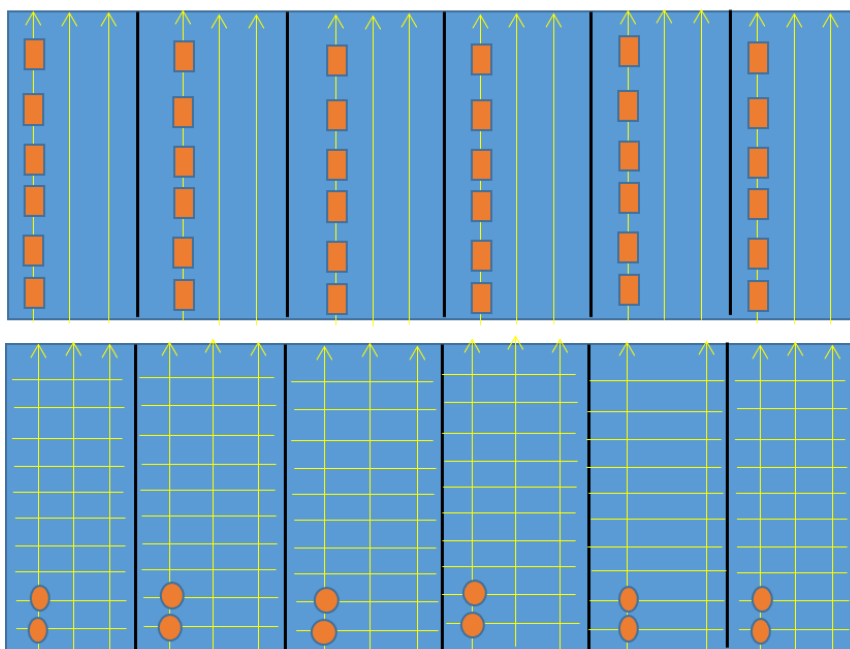


Figure 4.18: Flat plots survey method at all trials.

A 50-m tape measure was used for both methods to determine placement of the quadrants for density measurement and for frequency (point-foot method). This was incorporated to ensure similar survey placement in all plots, thereby ensuring that

sufficient repetitions were achieved for quantifiable and comparative results. The number of repetitions was related to the size of the plot and was therefore different between 10 x 10 m and 8 x 4 m plots, for example. Furthermore, flat plots were compared to flat plots and with slope plots to ensure that comparative results were obtained (Table 4.4).

Table 4.4: Summary of field survey sites, methods and dates. TSF: tailings storage facility.

Site	Density (repetitions per plot)	Frequency (1 m intervals)	Survey dates
Crown gold TSF – flat plots 2015 (10 x 10 m)	18 quadrants (50 x 50 cm)	30 repetitions per plot	Apr., Aug. 2015; Apr., Aug. 2016
Crown gold TSF – slope plots 2015 (8 x 4 m)	12 quadrants (50 x 50 cm)	24 repetitions per plot	Apr., Aug. 2015; Apr., Aug. 2016
Rooikraal gold TSF – flat plots 2015 (5 x 5m)	18 quadrants (50 x 50cm)	30 repetitions per plot	Apr., Aug. 2015; Apr., Aug. 2016
Rooikraal gold TSF – slope plots 2015 (5 x 5 m)	12 quadrants (50 x 50 cm)	30 repetitions per plot	Apr., Aug. 2015; Apr., Aug. 2016
Paardekraal platinum TSF – slope plots 2015 (6 x 6 m)	12 quadrants (50 x 50 cm)	18 repetitions per plot	Apr., Aug. 2015
North-West University greenhouse platinum tailings – flat plots 2016 (1 x 1 m)	9 quadrants 30 x 30 cm	30 repetitions (10 cm intervals on 3 separate transects)	Apr., Aug. 2016
Crown gold TSF – flat plots 2016 (10 x 10 m)	18 quadrants (50 x 50 cm)	30 repetitions per plot	Apr., Aug. 2016
Crown gold TSF – slope plots 2016 (8 x 4 m)	12 quadrants (50 x 50cm)	24 repetitions per plot	Apr., Aug. 2016
Rooikraal gold TSF – flat plots 2016 (10 x 5 m)	18 quadrants (50 x 50 cm)	30 repetitions per plot	Apr., Aug. 2016
Rooikraal gold TSF slope plots 2016 (10 x 5 m)	18 quadrants (50 x 50cm)	30 repetitions per plot	Apr., Aug. 2016

Chapter 5

Results and discussion

5.1 Introduction

This chapter presents the results from the four trial sites at Crown and Rooikraal gold mine tailings storage facilities (TSFs), Paardekraal platinum TSF and the North-West University (NWU) nursery platinum bulk bags that contained the same tailings material as Paardekraal platinum TSF. The germination, growth and establishment (survival after first season) and second-generation growth of species with coated and non-coated seed used for re-vegetation are described for the trials that were established on the slope and flat areas of TSFs as described in Chapter 4. The soil sample analysis results from each TSF are also described.

5.2 Field trials

Field surveys were conducted over four periods (see Chapter 4) to establish the seed germination, growth and establishment of the vegetation (survival in the second season). The surveys were carried out in April to determine germination and growth and then again in August to determine the survival rate after the dry winter months. The number of seed/kilogram for coated and non-coated seed was counted and compared for each species to establish the number of species that germinated and survived when using viable seed for the rehabilitation of gold and platinum mine TSFs (Figure 5.1).

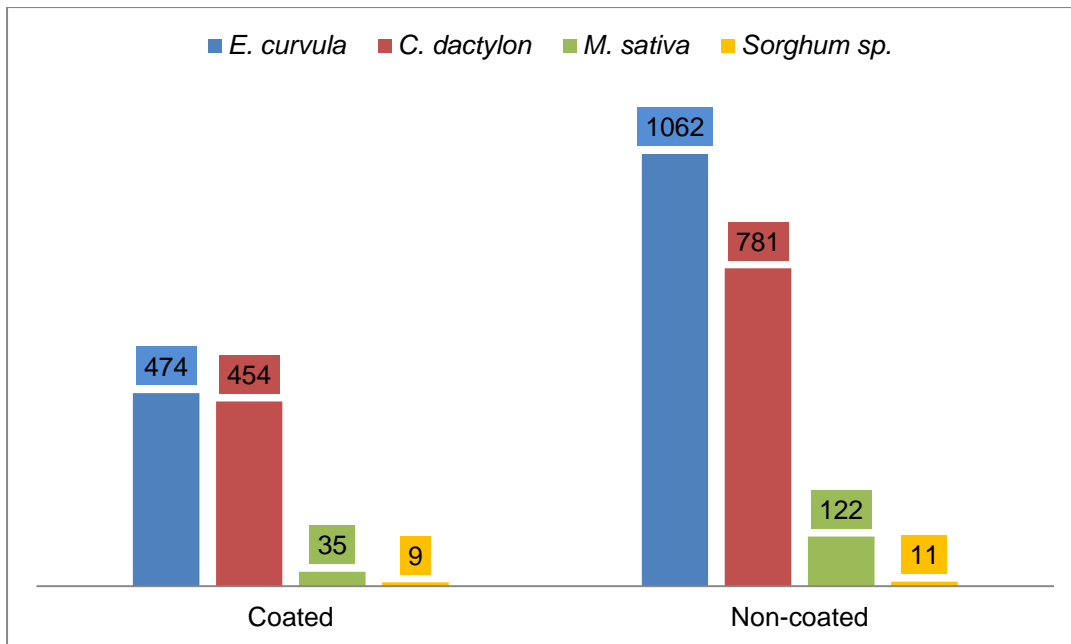


Figure 5.1: Viable seed/m² for coated and non-coated seed of *Eragrostis curvula*, *Cynodon dactylon*, *Medicago sativa* and *Sorghum sp.*

5.2.1 Frequency

The frequency of plants that established from the coated and non-coated seed for the two trial areas (flats and slopes) was determined for April (end of summer) and August (winter, to determine survival) over the two sampling seasons (2015 and 2016) at all sampling sites as seen in Figures 5.2 and 5.3.

5.2.1.1 Sites at Crown gold TSF

As normally conducted during the rehabilitation procedure by Agreenco Environmental Projects, the slope areas on the TSFs were irrigated and covered by a mulch layer to stimulate germination and growth (see section 5.2, Chapter 4). The flat areas were, however, not irrigated but were covered by a layer of compost and mulch. The germination and establishment of the coated and non-coated species sown on the slope with irrigation were compared to the flat surface areas, which were kept under dryland conditions (Figures 5.2 and 5.3). Differences could be identified between slope and flat plots after germination (April 2015).

For the non-coated seed of *E. curvula*, *C. dactylon* and *M. sativa*, the germination was on average 7.7 times better (in terms of plant numbers) on the slope plots than on the flat plots and 16.3 times higher when coated seed were used. The low germination results of the sown-in species on the flat surface plots that were not covered by mulch created an opportunity for opportunistic species transported via compost to establish. These included the annual rye grass (*Lolium multiflorum*) and other weed species. These species dominated the plots on the flat surface. This showed the importance of where or what type of compost is sourced and used during the rehabilitation process, as the seedbank in the compost might suppress the germination and establishment of the re-seeded species, especially during the short-term.

After the winter survey (August 2015), coated and non-coated species of *E. curvula* and *C. dactylon* showed a slight increase, especially on the flat surface plots (Figure 5.3). The survival of the re-seeded *M. sativa* was high in August 2015. Both the coated and non-coated plants of *E. curvula* and *C. dactylon* remained high in the flat surface plots after the rainy season as their abundance was still high after the April 2016 survey (Figure 5.3). This positive result showed that these two species were abundant in the seedbank, even after winter in the second season (August 2016) (Figure 5.3).

Similar results were obtained for the slope plots (Figure 5.2). The sown-in species (coated and non-coated) for *E. curvula* and *C. dactylon* were still high after the second season (August 2016), whereas *E. tef* and *M. sativa* decreased or even disappeared, as these are annual (*E. tef*) and semi-perennial (*M. sativa*) plants. The lower germination and establishment of the sown-in species on the slope plots could be ascribed to the surface erosion that occurred during the survey period and inter-species competition for nutrient availability and sunlight (Jim, 2001). Of the species sown, coated and non-coated *C. dactylon* and *E. curvula* were the best species to use when rehabilitating flat or slope surfaces of the gold mine TSFs.

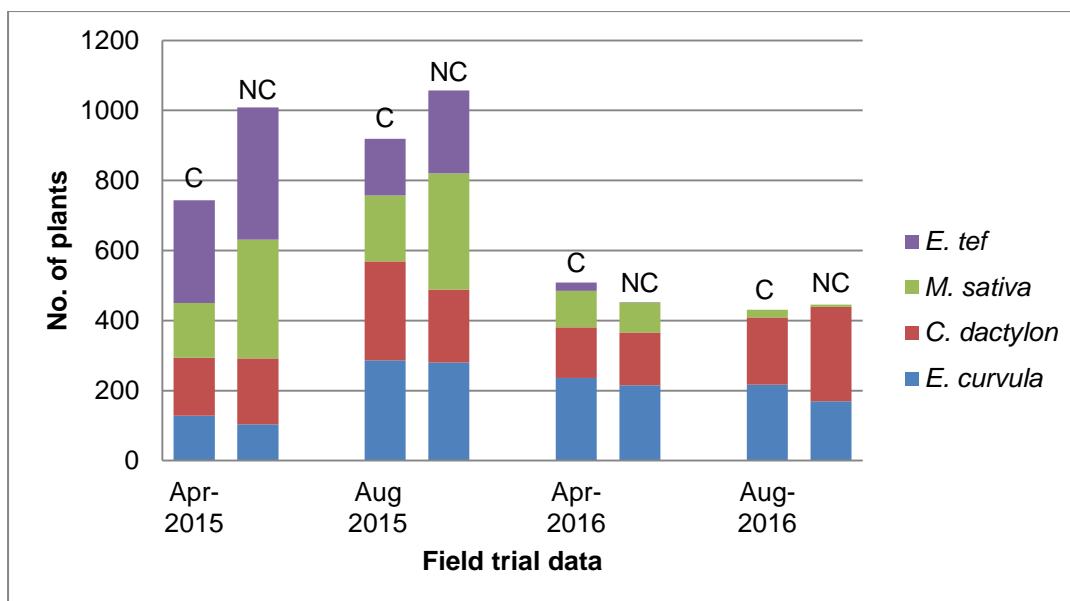


Figure 5.2: Comparison of the number of plants at Crown gold tailings storage facility slope plots (coated (C) vs. non-coated (NC) seed frequency) in 2015 and 2016 for *Cynodon dactylon*, *Eragrostis curvula*, *E. tef* and *M. sativa*.

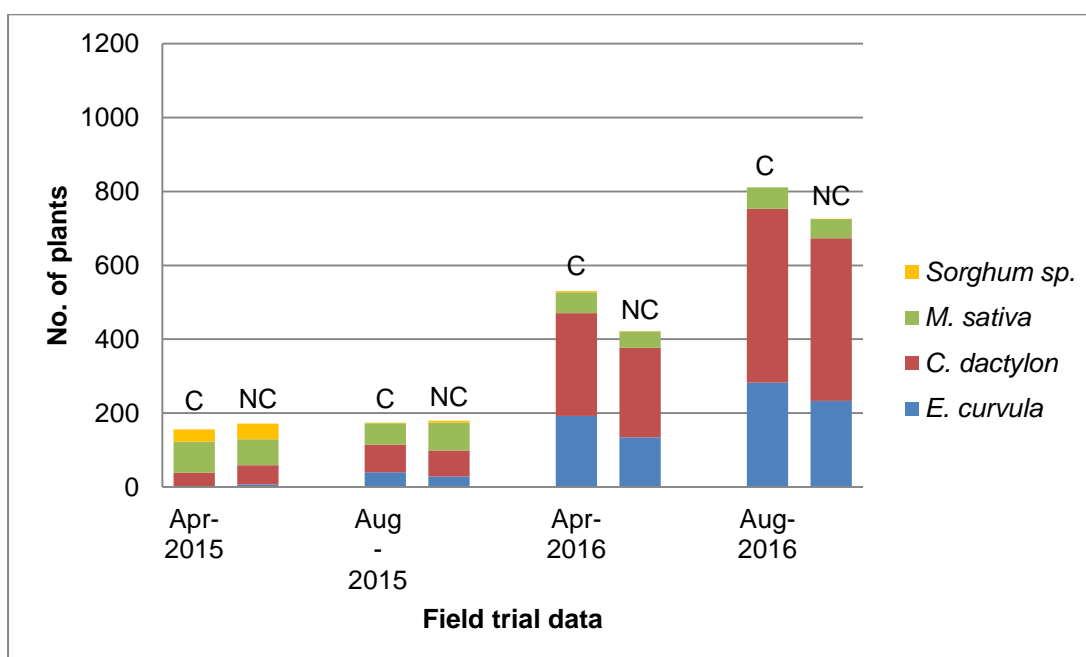


Figure 5.3: Comparison of the number of plants at Crown gold tailings storage facility flat plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for *Cynodon dactylon*, *Eragrostis curvula*, *E. Sorghum sp.* and *M. sativa*.

5.2.1.2 Rooikraal gold mine TSF

Significant differences between coated *E. curvula* occurred from April 2015 to April 2016 on the slope plots. *Eragrostis curvula* seedlings from coated seed decreased from 305 (total germinated plants in plots) in April 2015 to only 137 adult plants

surviving till April 2016, whereas the seedlings of non-coated *E. curvula* also decreased, but slightly increased again till April 2016 (Figure 5.4). Seed of *C. dactylon*, however, increased substantially in plots sown with coated seed on the slope plots, from 87 seedlings in April 2015 to 271 adult plants in April 2016 (Figure 5.4). Forage sorghum and *M. sativa* reacted similarly. Both species produced high numbers initially as expected (especially from an annual such as the *Sorghum* species) and thereafter decreased over time to reach similar numbers of adult plants (Figure 5.4). Although both species declined over time, the successful establishment initially aided the repair of soil nutrient availability and provided protection wind and water erosion to the other species against. Results are also shown in Figures 5.6–5.9.

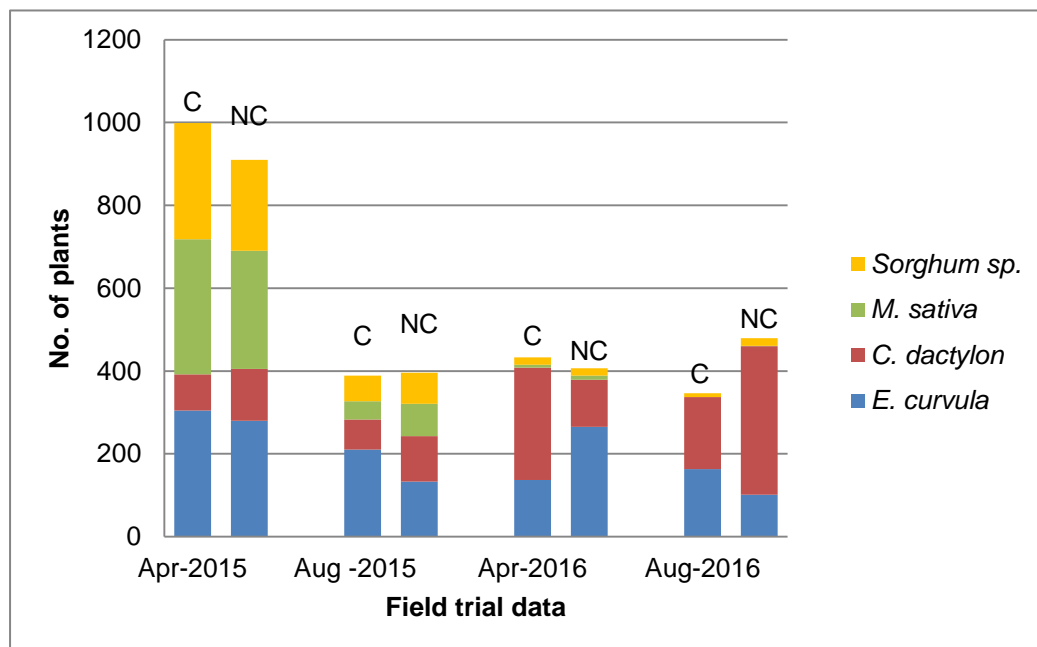


Figure 5.4: Comparison of the number of plants at Rooikraal gold tailings storage facility slope plots (coated (C) and non-coated (NC) seed frequency in 2015 and 2016 for *Cynodon dactylon*, *Eragrostis curvula*, *M. sativa* and *Sorghum* sp.

Similar to the results from the slope plots, coated *E. curvula* seed had very high germination rates at the first survey (April 2015) when compared to non-coated seed of the same species (402 vs. 250 seedlings) (Figure 5.5). Coated *C. dactylon* seed, on the other hand, showed lower germination rates than non-coated seed but increased substantially, whereas the *E. curvula* population decreased towards the April 2016 survey. Non-coated *C. dactylon* seed decreased with an increase in *E. curvula* adult plants from April 2015 to April 2016 (Figure 5.5). This difference could

be due to the shade caused by the larger *E. curvula* tufts and to the fact that *C. dactylon* species establish well in open, bare areas. Similar to the results for the slope plots at the gold TSFs at the Crown study site (Figure 5.2), *C. dactylon* and *E. curvula* were the best species to re-seed in rehabilitation at Rooikraal TSF, especially coated seed, as they had the highest survival rates in August 2016 (Figure 5.5).

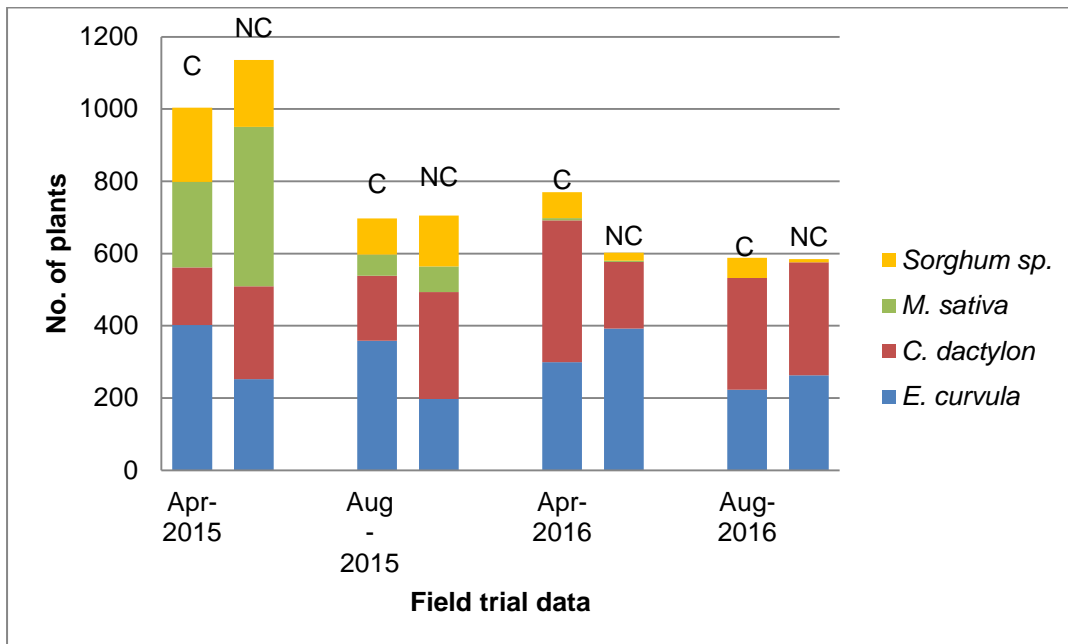


Figure 5.5: Comparison of the number of plants at Rooikraal gold tailings storage facility slope flat plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for *Cynodon dactylon*, *Eragrostis curvula*, *M. sativa* and *Sorghum sp.*



Figure 5.6: Rooikraal TSF pre-amelioration and seeding (Photo: H Taute, February 2015).



Figure 5.7: Rooikraal TSF first survey for germination results (Photo: H Taute, April 2015).



Figure 5.8: Rooikraal TSF second survey for growth and survival results (Photo: H Taute, August 2015); damage due to tailings spillage indicated by the arrow.



Figure 5.9: Rooikraal TSF final survey for survival and progeny seed growth. (Photo: H Taute, August 2016).

5.2.1.3 Paardekraal and North-West University (nursery) platinum TSF

As mentioned previously, the trial started at the platinum TSF of Paardekraal near Rustenburg. Unfortunately, the field trial at this location had to be suspended and moved to the nursery at the NWU, as researchers were not allowed on the Paardekraal TSF site after a change in management in August 2015. The germination of seed from the field trial which was surveyed during April 2015 was then compared to the germination of seed in the bulk bags in the NWU nursery, which had the same material as the TSF at Paardekraal. The only difference was that the field trials at Paardekraal were under dryland conditions, whereas the trials at the nursery were irrigated. This difference in better soil moisture conditions at the nursery could be seen in the higher germination rates in the April 2016 survey (Figure 5.10). The germination (April 2016) and survival (August 2016) of the coated seed of *E. curvula*, *C. dactylon* and *M. sativa* were slightly higher than that of the non-coated seed of the same species (Figure 5.10). Coated *C. dactylon* and *M. sativa* seed initially performed better under extreme stress conditions in Rustenburg than did coated seed of the same species at the NWU, whereas their non-coated counterparts performed better at the NWU. This led to the hypothesis that the coating of these species enable them to better survive high temperatures and low rainfall occurrences. Similarly, coated forage sorghum germinated better than non-coated sorghum at Paardekraal.

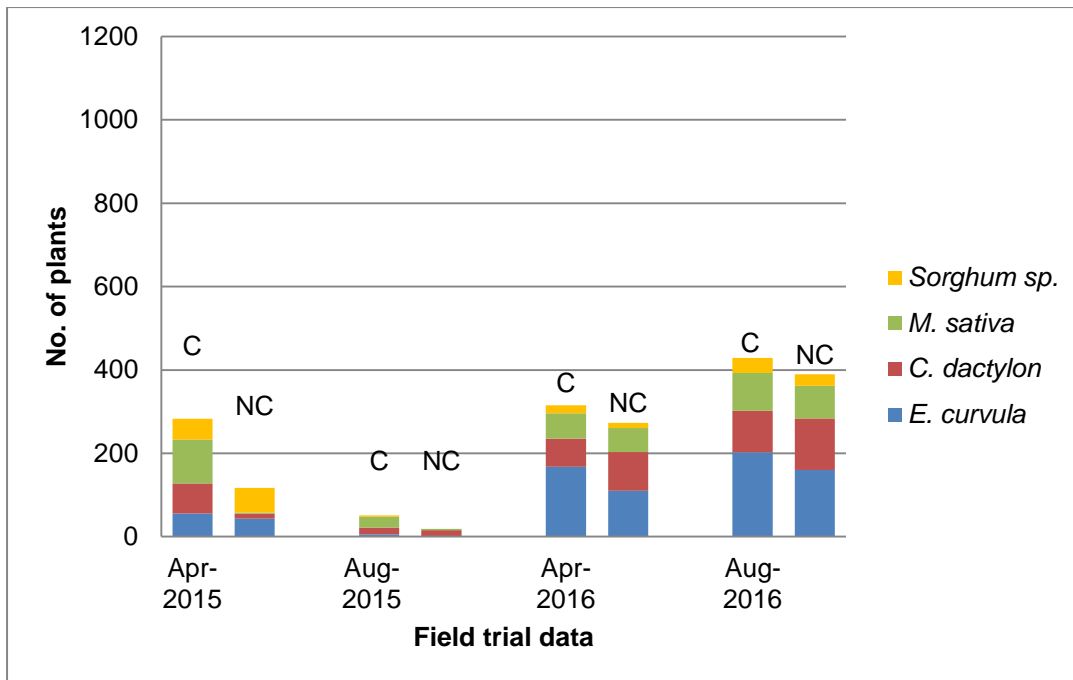


Figure 5.10: Comparison of the number of plants at the platinum tailings storage facility plots (coated (C) and non-coated (NC) seed frequency) in 2015 and 2016 for *Cynodon dactylon*, *Eragrostis curvula*, *M. sativa* and *Sorghum sp.*

5.2.2 Density

Species dynamics and competition are major factors determining the success of re-seeded species in any land rehabilitation project, especially if a mixture of annual and perennial species are sown (Sharitz & McCormick, 1973). Normal environmental management plan specifications state that the species diversity should be monitored over time as part of the rehabilitation process. Another factor of importance is the difference in sowing rate, especially if annuals, such as *E. tef*, and perennials, such as *E. curvula*, are used. Normally the sowing rate of annuals is lower due to the high seed mass and the fact that these species germinate and establish must faster (Westoby *et al.* 2002). These factors were considered during the establishment of the trials for this study. In this section, the density of coated and non-coated species that were used in the re-seeding trials at the study sites is discussed. This shows the interaction of species over the two-year trial period and will add to the explanation of the dynamics and importance of each species used in the rehabilitation process.

5.2.2.1 Crown gold TSF density results (coated vs. non-coated seed)

From Figures 5.11 and 5.12, it was observed that all species used in the re-seeding experiment were viable, contributing to the higher biodiversity on Crown gold TSFs, which were previously devoid of any seedbank. As expected, *E. tef* started to decrease in density towards the end of 2015 and beginning of 2016 (Figure 5.11). Similar to the frequency data, the two species that had the highest density were *E. curvula* and *C. dactylon* in both the slope and flat surface plots (Figures 5.11 and 5.12). This proves that after the final survey a stable community of *E. curvula* and *C. dactylon* was encountered in most of the plots. Coated seed germinated slightly better than non-coated seed at the start (April 2015) and the density of the coated seed of *E. curvula* was 11% higher than that of the non-coated seed on the slopes at the end of the trial in August 2016 (Figure 5.11).

As mentioned previously, after the first year, rye grass (*Lolium multiflorum*), which was transported with the organic material used to cover the flat surface trials, dominated the sites (Figure 5.12A, B, E and F). However, after one year's growth, the rye grass disappeared, which allowed the sown-in species to establish. This positive result showed the capability of quality coated seed to survive in a hostile seedbed after some time in gold TSF material, even if dominated by another plant in the first season (Muller, 2014). The sown-in species were also able to produce viable seed in the second season. The density of species at the end of the trial (August 2016) were similar to the results found at the slope surface trials, namely that few *M. sativa* plants remained, no sorghum survived and the dominance of *E. curvula* and *C. dactylon* plants (Figure 5.11 and 5.12).

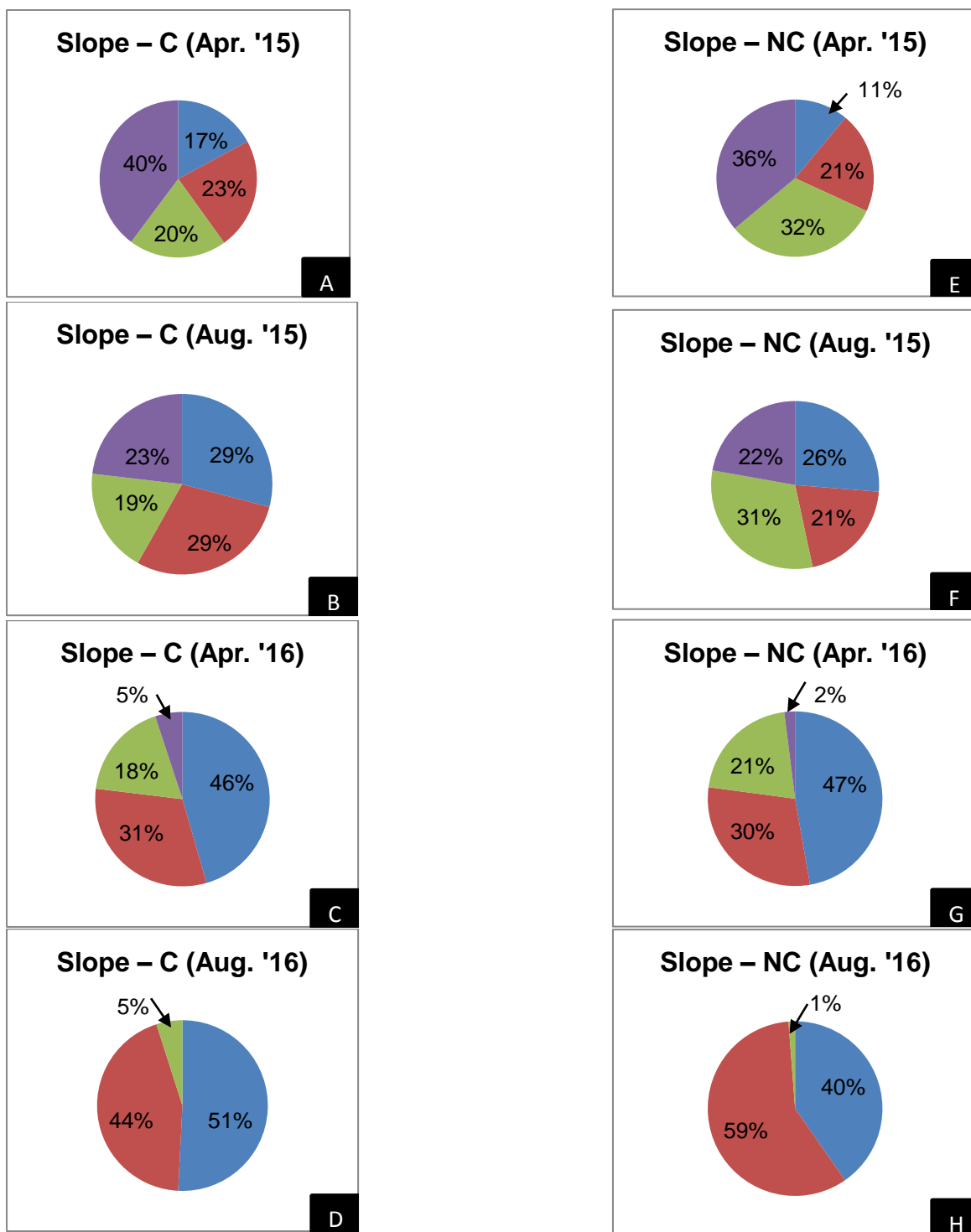


Figure 5.11: Density comparisons between coated (C) and non-coated (NC) seed in slope plots at Crown gold tailings storage facility (2015–2016). ■ *Cynodon dactylon*; ■ *Eragrostis curvula*; ■ *E. tef*; ■ *Medicago sativa*.

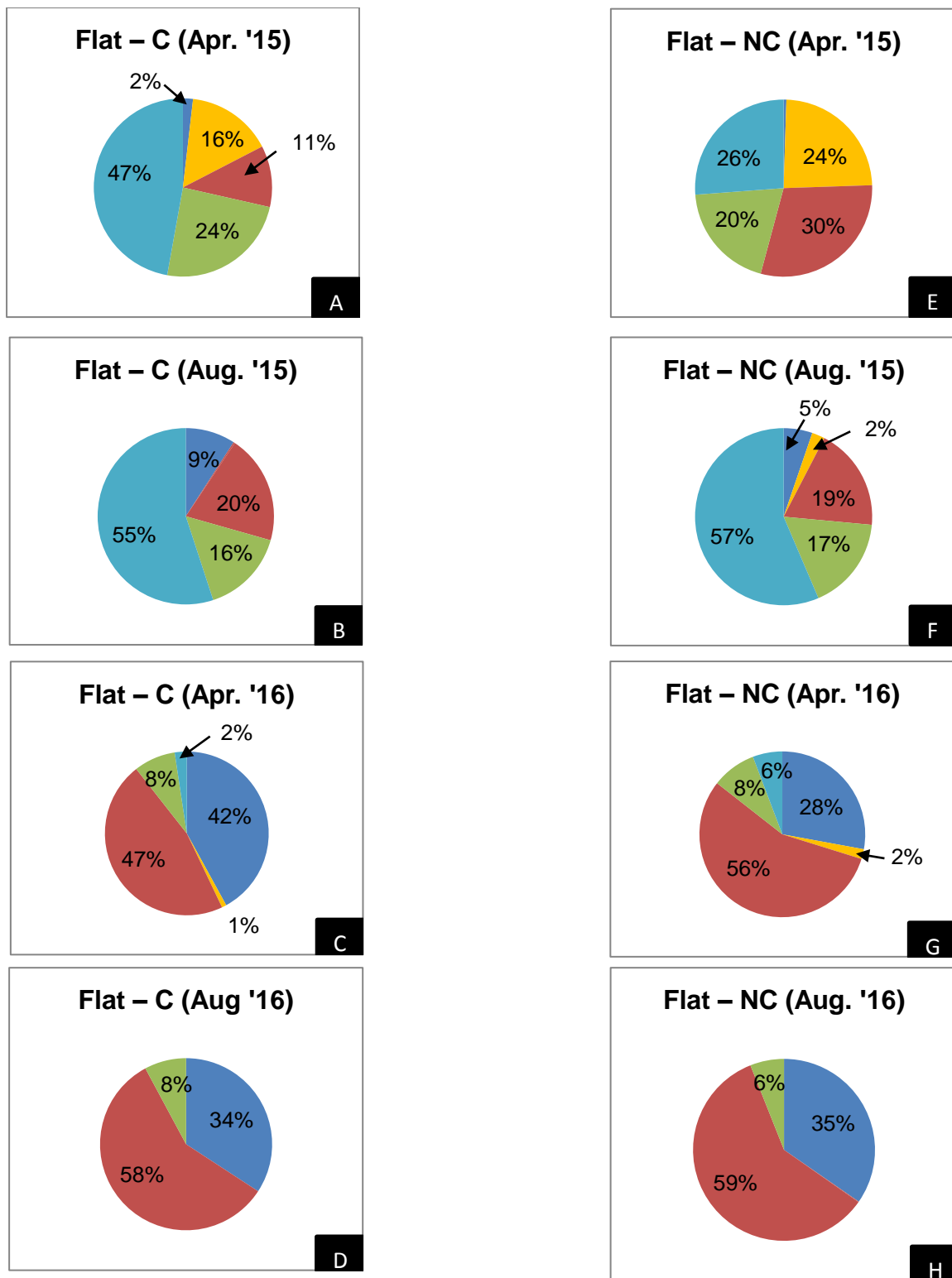
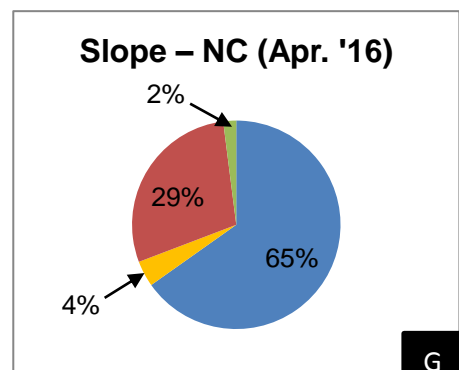
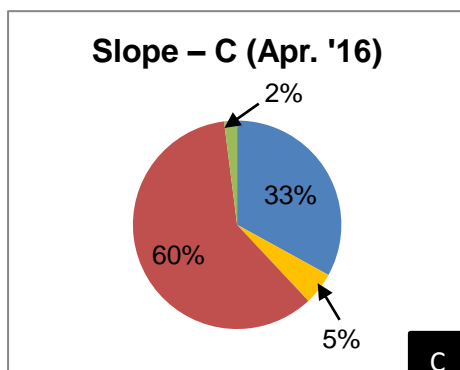
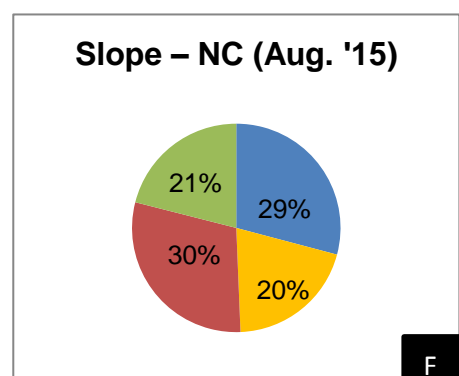
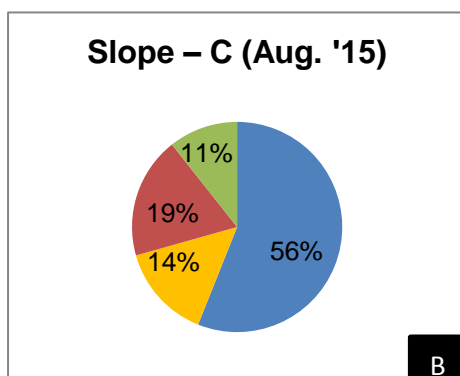
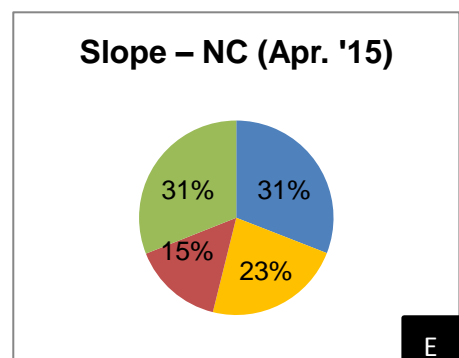
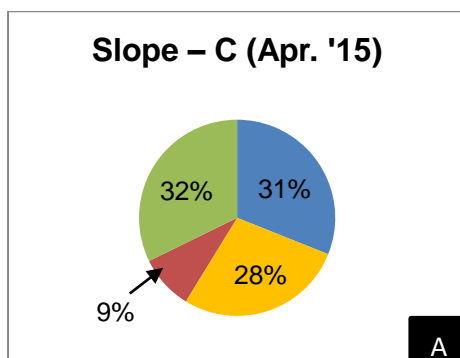


Figure 5.12: Density comparisons between coated (C) and non-coated (NC) seed in flat plots at Crown gold tailings storage facility (2015–2016). ■ *Cynodon dactylon*; ■ *Eragrostis curvula*; ■ *Lolium multiflorum*; ■ *Medicago sativa*; ■ *Sorghum sp.*

5.2.2.2 Rooikraal gold TSF density results (coated vs. non-coated seed)

The density of the species at the Rooikraal gold TSF showed results similar to those of the Crown gold TSF, namely a diverse initial germination mix of species followed by the domination of perennial species (Figures 5.13 and 5.14). Interestingly, the April 2016 and August 2016 results for the slope trials showed complete opposites for coated and non-coated plots. The coated *C. dactylon* dominated with 60% over *E. curvula* (33%), whereas non-coated *E. curvula* had a density of 65%, whereas that of *C. dactylon* was 29% (Figure 5.13). After winter during the August 2016 survey, the situation changed in that plots where coated seed were sown stabilised with similar densities of *E. curvula* and *C. dactylon*, with densities of non-coated *C. dactylon* much higher, at 74%, than for non-coated *E. curvula*, at a density of only 21% (Figure 5.13H).



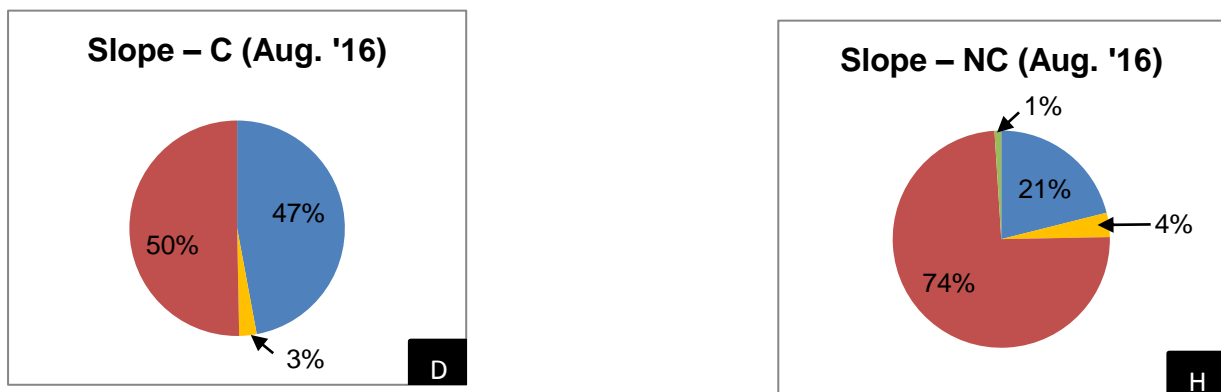


Figure 5.13: Density comparisons between coated (C) and non-coated (NC) seed in slope plots at Rooikraal gold tailings storage facility (2015–2016). ■ *Cynodon dactylon*; ■ *Eragrostis curvula*; ■ *Medicago sativa*; ■ *Sorghum sp.*

The densities of the coated species at the Rooikraal TSF on the flat surface plots showed similar results to the densities of species on the slope plots, especially after the first survey in April 2015 (Figure 5.14). The dominance of *E. curvula* and *C. dactylon*, however, appeared much sooner than in other plots or at the other trial sites. Similar densities were encountered between coated and non-coated plots, although non-coated *E. curvula* did decrease by 18% from April 2016 to August 2016 (Figure 5.14, G & H), whereas coated seed of the same species established faster and stabilised throughout the season. The density of *C. dactylon* increased substantially in most of the trials. This species occupied the open, bare patches and was able to survive in non-ameliorated TSF material spills. *Eragrostis curvula* and other species disappeared from these open areas as can be seen by the increase of *C. dactylon* in coated and non-coated plots during the August 2016 survey (Figure 5.14).

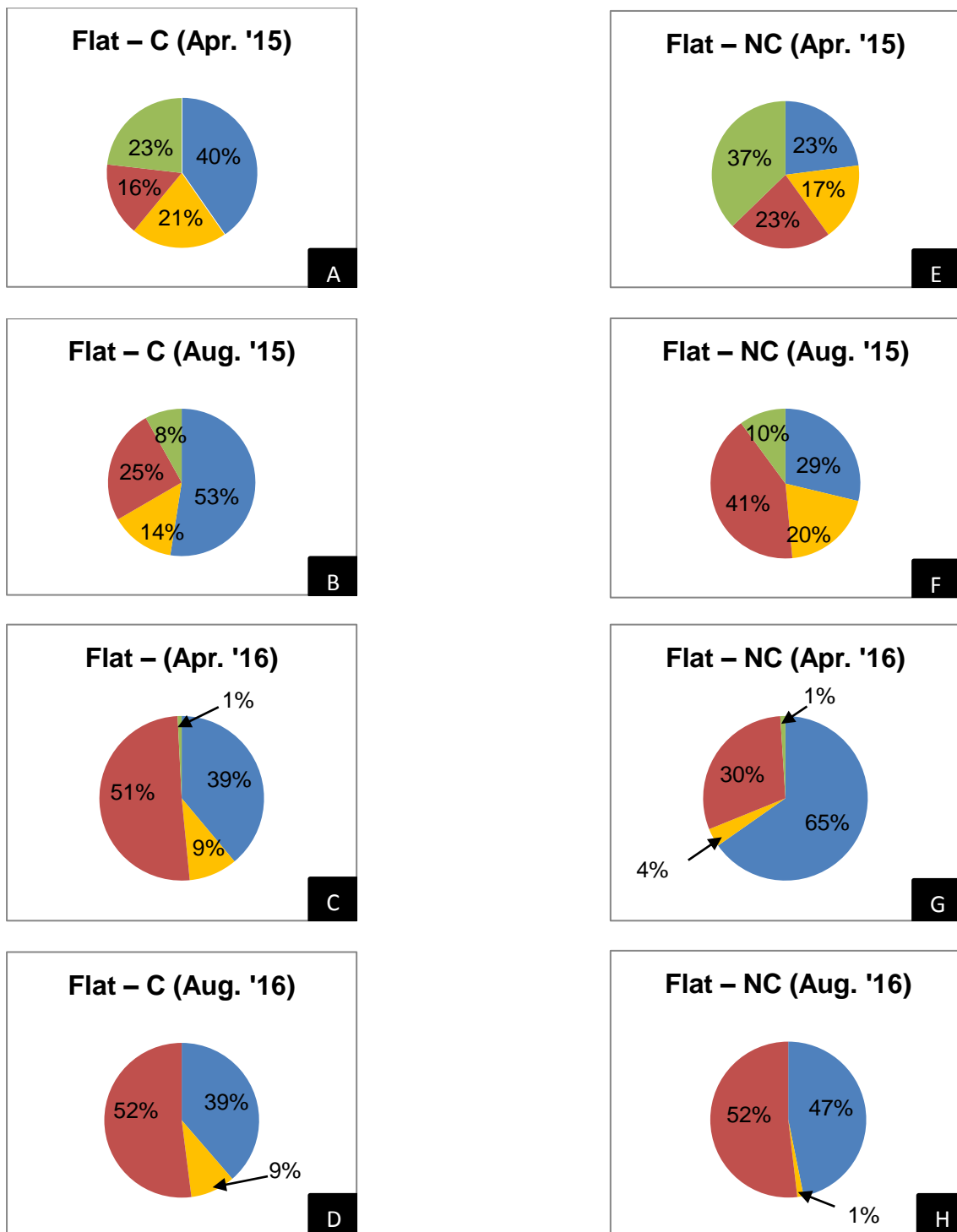


Figure 5.14: Density comparisons between coated (C) and non-coated (NC) seed in flat plots at Rooikraal gold tailings storage facility (2015–2016). ■ *Cynodon dactylon*; ■ *Eragrostis curvula*; ■ *Medicago sativa*; ■ *Sorghum sp.*

5.2.2.3 Platinum TSF density results (coated vs. non-coated seed)

The species density for both the coated and non-coated seed was quite high at first during the April 2015 at the field trial carried out at Paardekraal platinum TSF (Figure 5.15A & C). The area where the trial was carried out experienced a drought period with no/little rain, which led to poor results in the species density of August 2015. Mainly non-coated sorghum survived under the dryland conditions in the field trial (Figure 5.15D).

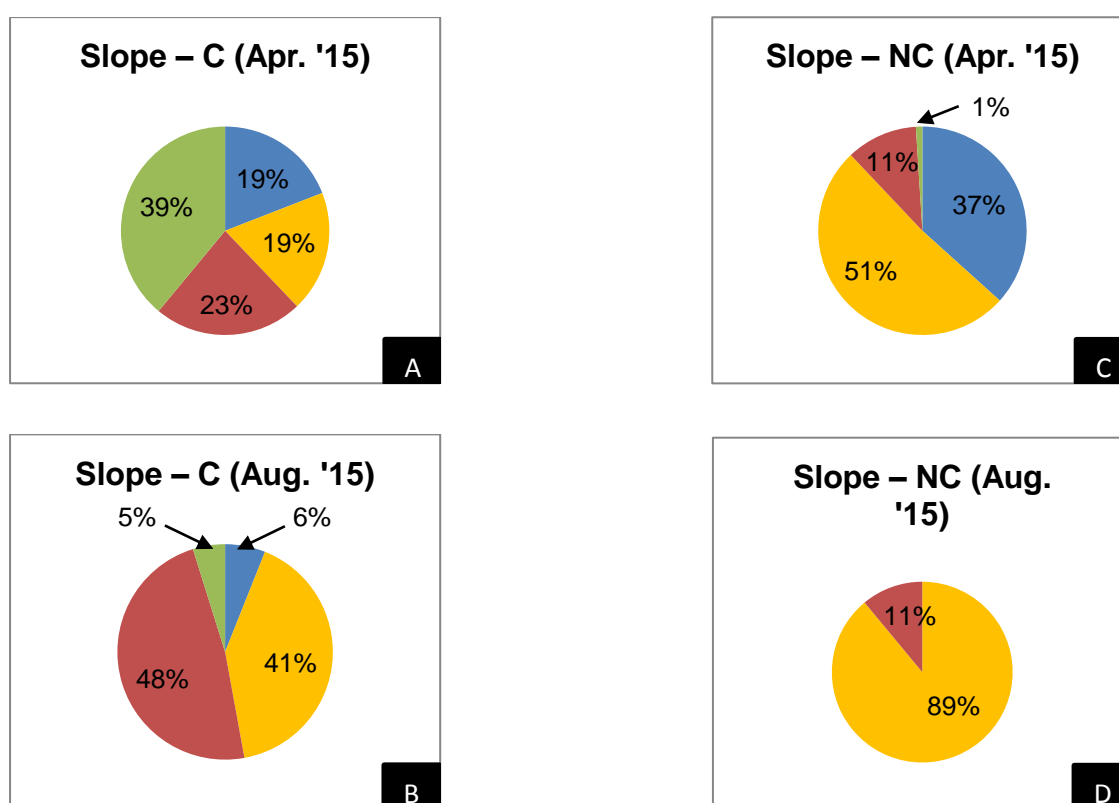


Figure 5.15: Density comparisons between coated (C) and non-coated (NC) seed in slope plots at Paardekraal platinum tailings storage facility (2015). ■ *Cynodon dactylon*; ■ *Eragrostis curvula*; ■ *Medicago sativa*; ■ *Sorghum* sp.

The density surveys carried out in the bulk bags at the NWU nursery showed that the density of non-coated *C. dactylon* (Figure 5.16C & D) was slightly higher than that of the coated seed of the same species, but that the density of coated *E. curvula*, *M. sativa* and *Sorghum* sp. was higher from April 2016 to August 2016 (Figure 5.15A & B). Otherwise no major differences were encountered between coated and non-coated seed for these trials.

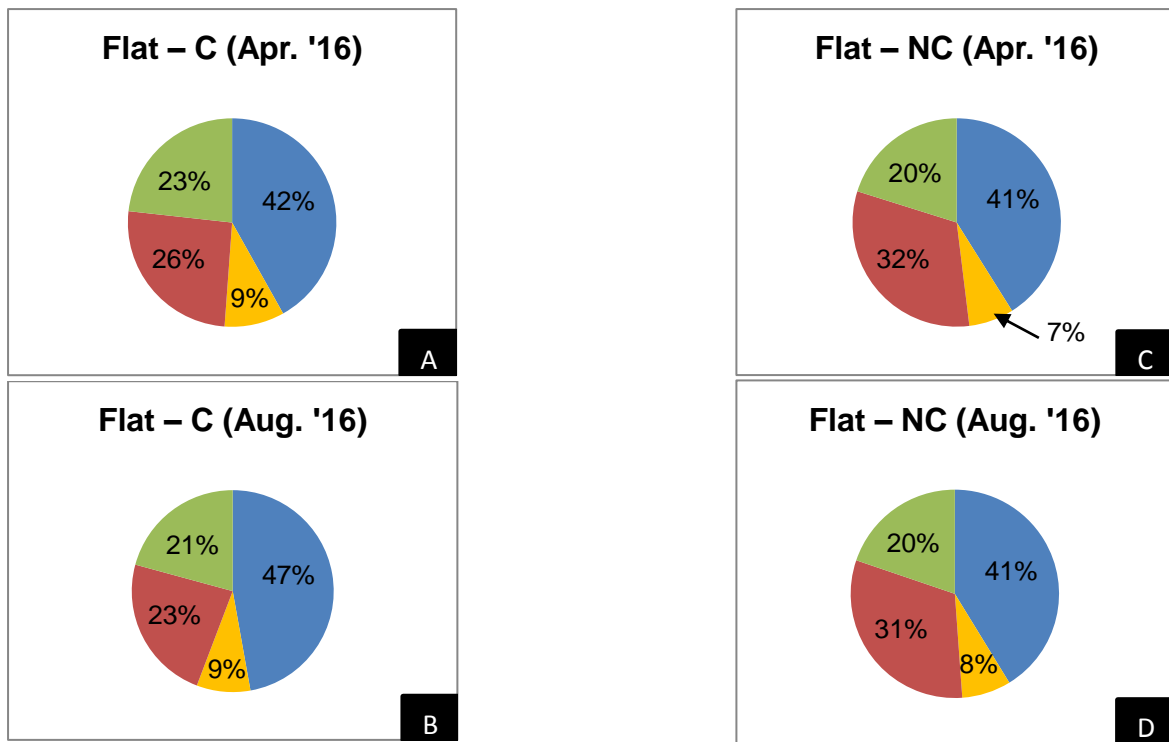


Figure 5.16: Density comparisons between coated (C) and non-coated (NC) seed in plots at the North-West University nursery (platinum tailings material) (2016). ■ *Cynodon dactylon*; ■ *Eragrostis curvula*; ■ *Medicago sativa*; ■ *Sorghum sp.*

5.3 Soil analysis

As previously mentioned, soil sampling and analysis were undertaken prior to soil amelioration and one year after soil amelioration was carried out. The impact of amelioration on the soil quality was determined by comparing these two analyses. Soil quality could have influenced vegetation germination and establishment. The following soil properties were analysed, namely cation exchange capacity (CEC), which will influence the availability of macro- and micronutrients, the different micro- and macronutrients, which should strongly impact on the survival of plant species, the overall nutrient status to evaluate nutrient deficiencies, as well as soil parameters vs. pH levels and EC. The true levels of critical elements such as plant-available phosphorus, potassium and magnesium were also analysed. The particle size distribution (PSD) to establish the sand, clay and silt fraction, criteria for the use of fertiliser and coating effectiveness because of leaching probabilities, dust formation, water infiltration capabilities and erosion was also measured. The redundancy analysis (RDA) ordination in the CANOCO software package (Ter Braack, 1988) was used to determine any correlations between soil characteristics, species re-seeded

(coated and non-coated seed), study sites at the gold and platinum TSFs and whether the plots were situated on flat or slope surface of the TSF.

RDA is suited to short linear species-response gradients and non-sparse data sets. It involves calculating principal component analysis on a species data matrix by performing multiple regressions with a matrix of paired environmental variables (Kent, 2011). The RDA diagrams allow Eigen values to be calculated. These values represent the contribution (relative) of individual part or components of a data set in relation to the total variance. The size of the Eigen value relative to the component is important as it indicates the value of correspondence. The soil sampling results are represented in Annexure A.

5.3.1 Crown gold TSF redundancy analysis results

Table 5.1: Redundancy analysis triplot legend

CrFCA15 and 16 – Crown flat coated April 2015 and 2016
CrFNcA15 and 16 – Crown flat non-coated April 2015 and 2016
CrSCA15 and 16 – Crown slope coated April 2015 and 2016
CrSNcA15 and 16 – Crown slope non-coated April 2015 and 2016
RFCA15 and 16 – Rooikraal flat coated April 2015 and 2016
RFNcA15 and 16 – Rooikraal flat non-coated 2015 and 2016
RSCA15 and 16 – Rooikraal slope coated 2015 and 2016
RSNcA15 and 16 - Rooikraal slope non-coated 2015 and 2016

For all the RDAs completed, a clear division between annual and perennial species was observed. *M. sativa* is a perennial but performed similarly to an annual species during the trials, namely with quick establishment and low density during the second growth season. In Figure 5.17 the CEC and base saturation indicated lower plant nutrient availability and S-value and calcium are correlated and correspond to the annual species (rye and sorghum) in the Crown flat coated April 2015 plots. Potassium and magnesium levels occurred in the non-coated 2016 plots and were correlated with the perennial *C. dactylon* and *E. curvula* species. This means that

these elements occurred in the amelioration and are necessary if these two perennial species are re-seeded and is supported by Romheld and Kirkby, 2010. The occurrence of sodium was a peculiar find, as no sodium was specifically added to the soil during fertiliser application. This element was present in the soil and also indicated a positive correlation with the re-seeding of perennial species (Figure 5.17).

CEC plays a major role in soil stability and structure and reaction of soil towards fertiliser (Hazelton & Murphy, 2007). Base saturation also plays an important role in soil sample classification and indicates the amount of exchangeable cations as a percentage of the CEC. As seen in the soil analyses, the base saturation for the majority of the sites were below 100% and therefore allowed Al^{3+} to form acidity.

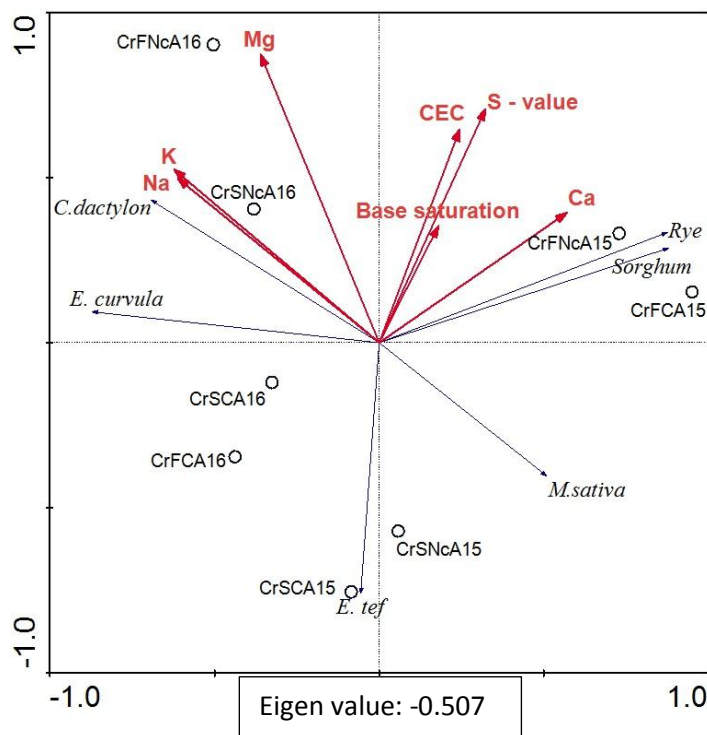


Figure 5.17: Crown gold tailings storage facility – cation exchange capacity (CEC) in relation to coated and non-coated plots (2015 and 2016).

Higher macronutrient values were encountered at the 2016 plots and were associated with perennial species as seen in Figure 5.18. These elements were needed in the amelioration to acquire a sustainable stand of trial species over the long-term. Similar to for the previous results for CEC, the annual plants were associated with the soil analysis sampled in 2015, before amelioration. Overall

macronutrient levels remained low in comparison to ideal nutritional values, but were positive when considering the lack of nutrients commonly encountered in gold TSF material. When considering the ammonium (NH_4) and ammonium nitrate (NO_3) levels, a decrease was seen from soil sampled in 2015 to that sampled in 2016 (Annexure B). NH_4 decreased from 0.28 mmol/l to 0 and NO_3 decreased from 0.27 to 0.09 mmol/l. NH_4 can convert to NO_3 in soils but overall levels of nitrogen remain very low when considering plant requirements. Although low, the levels of calcium, magnesium and phosphorus were again correlated with the perennial species sown after the amelioration that took place before the 2016 soil analysis. Calcium and magnesium also increased in the soil from 10.12 and 3.06 mmol/l to 11.12 and 9.58, respectively – due to the liming during amelioration. The association of *M. sativa* and NH_4 can be prescribed to the nitrogen fixation capabilities of this legume species, including the application of fertiliser in 2015. The presence of chloride can be attributed to the compost used during soil amelioration (Figure 5.18).

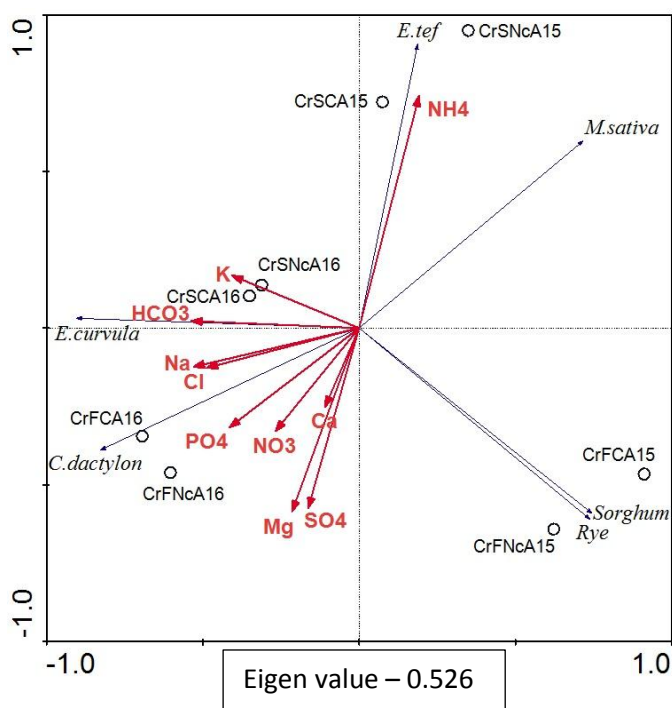


Figure 5.18: Crown gold tailings storage facility – macronutrient availability in relation to coated and non-coated plots (2015 and 2016).

The micronutrient availability is in part influenced by CEC, base saturation and EC of the soil (Horneck *et al.*, 2011). A clear increase in availability for copper, iron, zinc and manganese was encountered (Figure 5.19), but was more closely related to the

annual species, rye and *Sorghum* sp. Very low overall levels of all micronutrients were encountered. Most nutrient levels decreased over the trial period, except for boron, and EC increased in the 2016 sample analysis from 1 mmol/l to 11 mmol/l and 2.73 mS/cm to 4.59 mS/cm respectively. Boron can be toxic to vegetation in excessive amounts of above 2 ppm and should therefore be considered as a negative issue in these trials (Figure 5.19).

The soil pH was, as expected, very low for the gold TSFs at the Crown and Rooikraal study sites. The pH(H₂O) and pH(KCl) values varied between 3 and 4. The ideal soil pH values for good plant growth is considered to be between 6 and 8.2 (Horneck *et al.*, 2011). Amelioration using lime succeeded in raising the soil pH level to between 6 and 7, creating conditions more suitable for vegetation establishment and enabling the movement of plant-available nutrients.

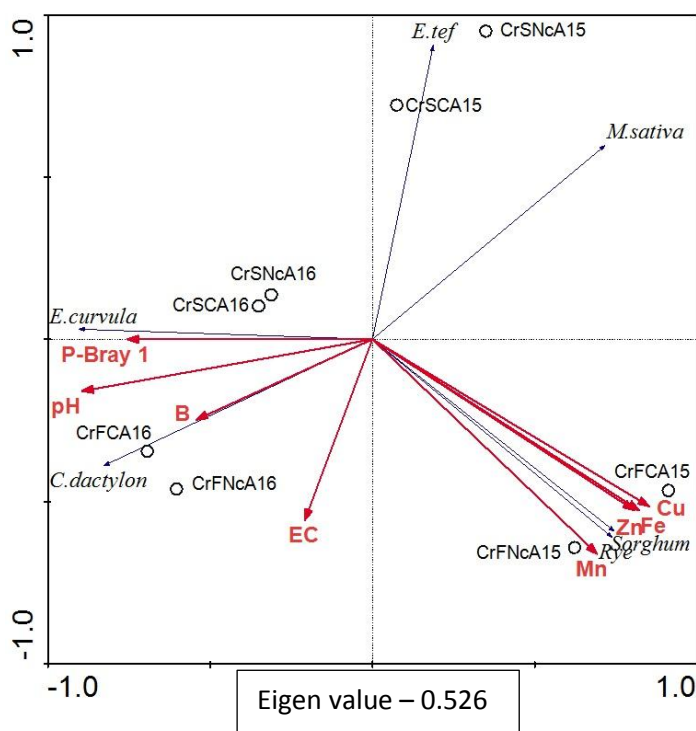


Figure 5.19: Crown gold tailings storage facility – micronutrient availability in relation to coated and non-coated plots (2015 and 2016).

The nutrient status analysis confirmed the data and results from the macro- and micronutrient levels obtained in the soil. An Olsen analysis was also completed to indicate the phosphorus levels. Phosphorus increased in all plots over the trial time period and grouped well with perennial species on flat and slope plots. The increase

in pH level and association with the perennial plants sown could also be seen for the 2016 analysis (Figure 5.20). Phosphorous formed part of the fertilizer used for amelioration and explains the presence thereof in the samples.

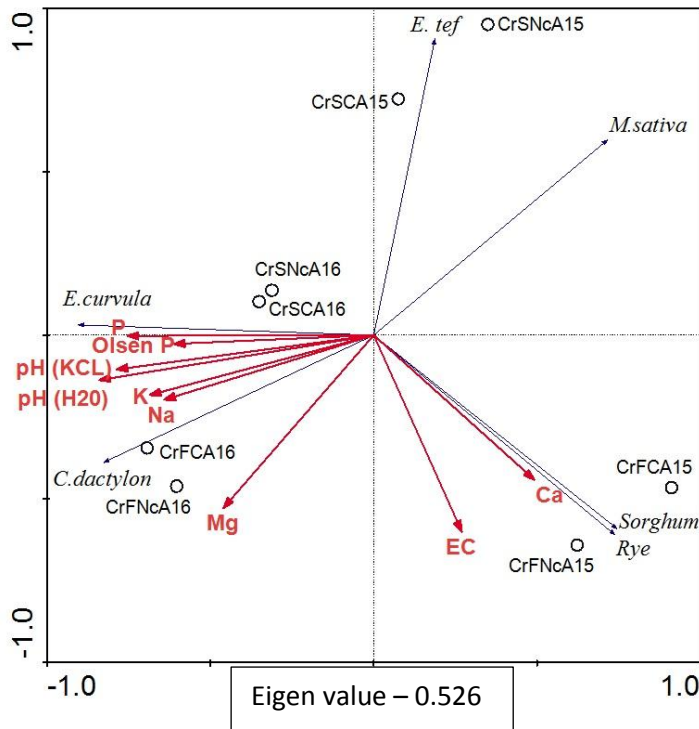


Figure 5.20: Crown gold tailings storage facility – nutrient status availability in relation to coated and non-coated plots (2015 and 2016).

The particle size distribution indicated that there were no particles with sizes >2 mm in the collected soil samples, i.e. the soil was very sandy. The soil properties consisted of 72–95% sand, 2–21.5 % silt and 0.4– 5.9 % clay. In this comparison, *E. tef*, *M. sativa* and *E. curvula* associated with higher sand percentages, whereas rye, *Sorghum* sp. and *C. dactylon* associated with higher percentages of silt and clay (Figure 5.21).

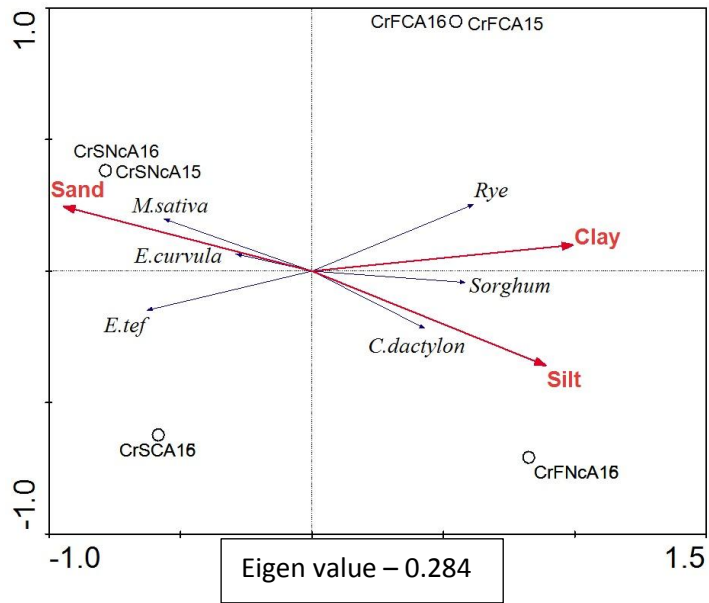


Figure 5.21: Crown gold tailings storage facility – particle size distribution in relation to coated and non-coated plots (2015 and 2016).

5.3.2 Rooikraal gold TSF redundancy analysis results

At the Rooikraal study site, the CEC was positive associated with *Sorghum* sp. and *M. sativa* on the right hand side of the x-axis, which is similar to the soil analysis found at the Crown sites, whereas the perennial *E. curvula* and *C. dactylon* species were more associated with the other elements. This correlation was distinct with such a high Eigen value of 0.747 (Figure 5.22). A clear distinction was visible in the RDA between the soil samples of 2015 (before soil amelioration) and 2016 (after soil amelioration), with the non-coated seed of *E. curvula* associated with the higher sodium, magnesium, potassium and base saturation levels.

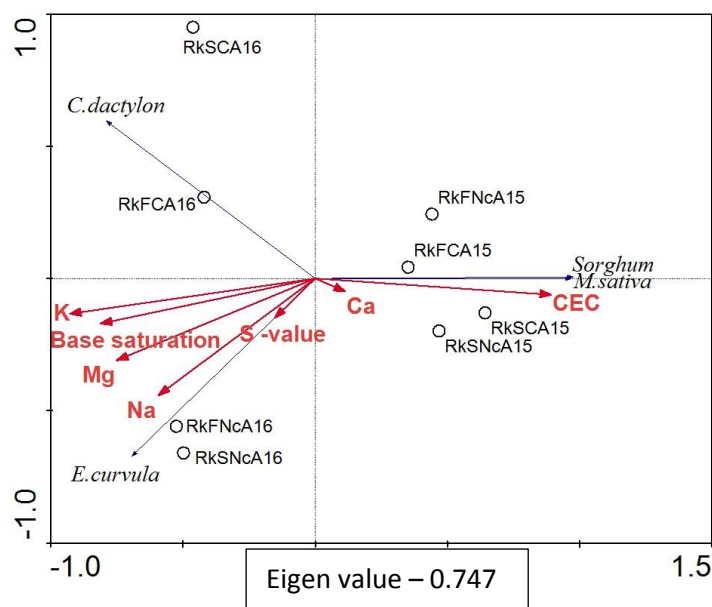


Figure 5.22: Rooikraal gold tailings storage facility – cation exchange capacity (CEC) in relation to coated and non-coated plots (2015 and 2016).

The soil samples at the Rooikraal site differed from the soil samples from Crown TSFs. At Rooikraal, the macronutrient levels were more positively correlated with the annual species (*Sorghum* sp.) and *M. sativa* on the right hand side of the x-axis (Figure 5.23). The occurrence of the two perennials, *C. dactylon* and *E. curvula* was more stable in the second year (2016 – left hand side of the x-axis), which correlates with the frequency and density data mentioned above. *Eragrostis curvula* was

associated with higher levels of magnesium, potassium and HCO_3 . Sodium appeared again in the soil sample, indicating the importance of this element in the fertiliser if these perennial species are to be used for the rehabilitation of gold mine TSFs.

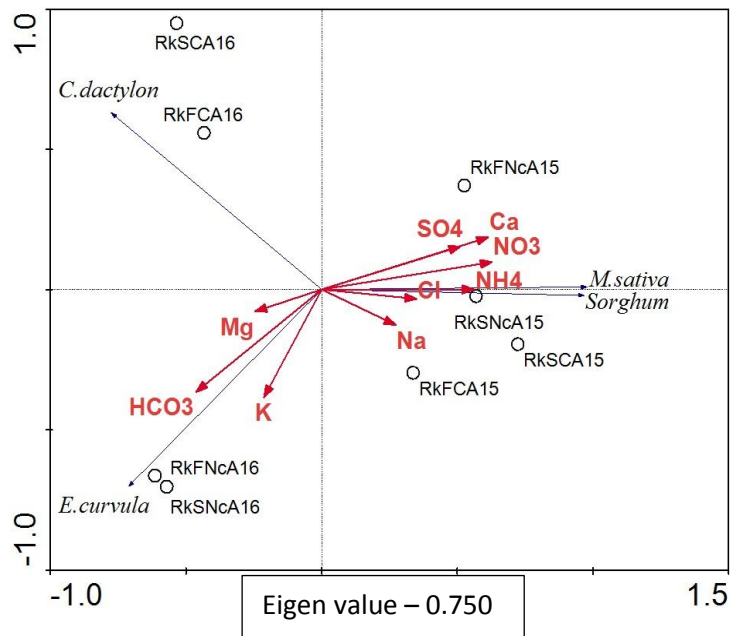


Figure 5.23: Rooikraal gold tailings storage facility – macronutrient availability in relation to coated and non-coated plots (2015 and 2016).

The micronutrient availability and distribution appeared more even in the soils of the Rooikraal TSFs than for the Crown gold TSFs, with lower levels of zinc, manganese and copper (Figure 5.24). As for the other plots mentioned above, the perennial species *E. curvula* and *C. dactylon* were associated with the soils analysed after amelioration in 2016 and the annual species (*Sorghum* sp.) and *M. sativa* were associated with higher EC, copper and iron levels in the soils sampled before amelioration in 2015. Non-coated *E. curvula* associated best with higher boron levels, whereas coated *C. dactylon* associated with higher manganese and zinc levels.

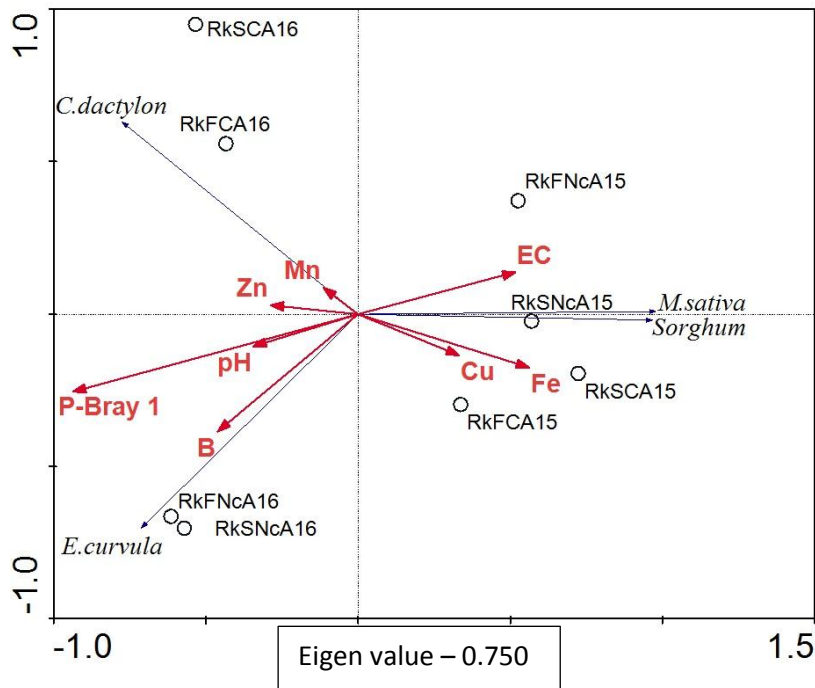


Figure 5.24: Rooikraal gold tailings storage facility – micronutrient availability in relation to coated and non-coated plots (2015 and 2016).

An increase in pH and sodium, magnesium, phosphorus and potassium levels in 2016 was evident in plots where non-coated seed of *E. curvula* were used (Figure 5.25). The same nutrients were positively associated with soils where coated seed of *C. dactylon* were used, but to a smaller extent. Sodium is commonly encountered in Witwatersrand TSFs due to the high levels in the ground water encountered in the area. *Sorghum* sp. and *M. sativa* were associated with 2015 plots of coated and non-coated seed, with higher levels of EC and calcium. The results correlated with population surveys conducted, where *Sorghum* sp. and *M. sativa* germinated and established well in the first year (2015), but decreased substantially in the following year (2016).

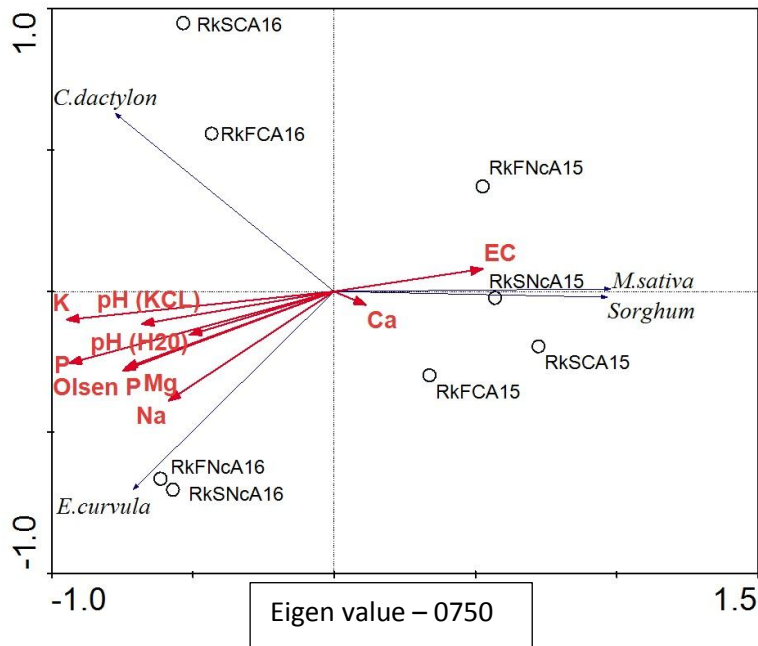


Figure 5:25: Rooikraal gold tailings storage facility – nutrient status availability in relation to coated and non-coated plots (2015 and 2016).

Similar to the trials of the Crown TSFs, the soils at Rooikraal did not have particle sizes larger than 2 mm in size, indicating that the soils were very sandy. The majority of soil consisted of sand particles (85–95%) followed by silt (2–9%) and clay (0.4–2.7%) (Figure 5.26). *Eragrostis curvula* again associated better with the sandy soils for the sites at Rooikraal TSFs, whereas *C. dactylon* and *Sorghum* sp. associated better to higher silt and clay soils.

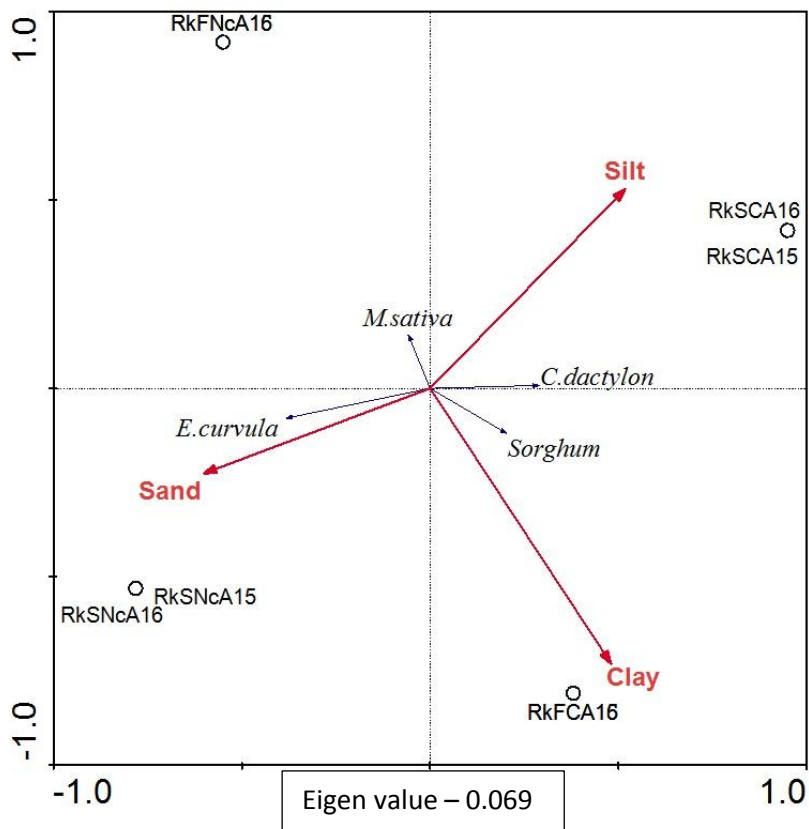


Figure 5.26: Rooikraal gold tailings storage facility – particle size distribution in relation to coated and non-coated plots (2015 and 2016).

5.3.3 Paardekraal and North-West University (nursery) platinum TSF redundancy analysis results

No RDA triplots were included for these trial sites as the species data (frequency and density) were considered sufficient to illustrate the impacts of platinum TSFs on vegetation establishment. The soil analyses of the Paardekraal platinum TSF is shown in Annexure A. When compared to the climatic data shown in Chapter 4, it is clear why very little growth was encountered at the Paardekraal site vs. the NWU nursery. Rustenburg suffered a continuous drought which very low rainfall and high average temperatures for 2014, 2015 and 2016.

5.4 Comparison of the soils at the Crown and Rooikraal TSFs

It is important to emphasise that soils were very site-specific and can differ between TSFs. Although the soils from the two gold TSFs at Crown and Rooikraal were

similar, especially regarding the soil particle distribution (both were sandy soils), the composition differed slightly in that the calcium content at Crown was significantly higher (2891 vs. 373 mg/kg) on slope and flat plots in 2015 and 2016 except for the slope coated plots at Crown, which decreased from 1823 mg/kg in 2015 to 685.5 mg/kg in 2016. Alternatively, the calcium content increased in the non-coated slope plots at Crown TSF from 1526 mg/kg (2015) to 2133 mg/kg (2016) (see Annexure A).

pH (H₂O and KCl) increased after amelioration at all trial sites and stabilised (as shown in Annexure A) at 6.09 to 8.32 except for the Rooikraal slope plots (coated and non-coated), which decreased to 4.58. Paardekraal exhibited high pH levels (7.16–8.4) throughout the trial as expected. Platinum trials also exhibited the highest sodium levels overall except for Crown flat coated plots in 2016. Significant differences in boron levels were found at Crown slope plots (coated and non-coated), which increased from 1 mmol/l in 2015 to 11 mmol/l in 2016. These were the only plots that showed a notable change in boron levels. Crown flat plots (coated and non-coated) exhibited elevated levels of iron in 2015 compared to all the other trial sites at Crown and Rooikraal. Coated flat plots at Crown contained 519.3 mmol/l and the non-coated plots contained 322.30 mmol/l, whereas the highest iron level in other plots measured 14.58 mmol/l (Crown slope coated plots). These levels decreased to 12 mmol/l in 2016.

Important, however, is that at both Crown and Rooikraal TSFs, the perennial species established much better after amelioration in 2016, whereas the annual species established well at the start of the rehabilitation phase. This emphasises the importance of using annual and perennial species in a mixture when rehabilitating.

Chapter 6

Conclusion and recommendations

6.1 Introduction

According to Van den Bergh and Zeng (2005), land degradation is the decrease in plant species diversity and associated impacts are low grass heights and vegetation cover. Cooke and Johnson (2002) state that the restoration of mined land in practice can largely be considered as ecosystem reconstruction or the re-establishment of the capability of the land to capture and retain fundamental resources. In restoration planning, it is imperative that goals, objectives and success criteria are clearly established to allow the restoration to be undertaken in a systematic way, while realising that these may require some modification later in light of the direction of the restoration succession. When combined with the Society for Ecological Restoration (SER) (2014) definition of ecological restoration, that it “is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed”, the necessity and the difficulty of mine rehabilitation is realised. For many rehabilitation projects, especially for the rehabilitation of mine tailings storage facilities (TSFs) for mining companies, it is important to establish vegetation cover in degraded areas or bare, denuded TSFs to decrease pollution or promote production potential and biodiversity Cooke and Johnson (2002). Degraded natural grazing lands (rangelands) normally still have a seedbank under the bare and denuded patches, which can be stimulated if the soil moisture regime is improved.

TSFs are, however, newly constructed by the mining operation that have different “soil” mediums depending on the ore that is being mined. These TSFs are mostly devoid of any seedbank and are either covered by a topsoil from different sources, which might contain a seedbank of the species that was growing in that environment, or a new growth medium, which is constructed on the flats and slopes by the rehabilitation company with re-seeding and the addition of mulch and/or organic material with specific amelioration actions depending on the soil type and its

composition. Mine TSFs are therefore mostly infertile and a new habitat and ecosystem has to be created by the rehabilitation activities.

The costs associated with these rehabilitation measures range from massive amelioration applications, infrastructure development, such as wind breaks and the addition of viable seed to completely revitalise the ecological structure and function. The latter mostly entails massive labour costs and penalties that can be incurred for non-compliance to environmental legislation and timeframes. Therefore, rehabilitation efforts often centre on fast establishment of cover to limit dust and erosion impacts, followed by limited monitoring and maintenance to ensure a sustainable, healthy ecosystem over the long-term.

Turner *et al.* (2006) describes the success of re-seeding grass species in natural veld conditions. Haagner (2008) links well with this research by combining natural veld re-seeding with rehabilitation practice and the impact thereof on re-seeding methods and success. Very little research has, however, been carried out to evaluate the use of coated seed in re-seeding practices on mine TSF. Brits (2007), Westcott (2011), Nel (2012) and Muller (2013) have studied the use of coated seed for rehabilitation, but their studies mostly included laboratory and nursery trials.

This study focussed on the comparison in germination, growth and survival of coated and non-coated seed in dryland conditions on gold and platinum mine TSFs. The results of this study will therefore add value to previous research by the authors mentioned above. The results will contribute to the knowledge of successful re-grassing of TSFs and identify gaps for future research to ensure the establishment of sustainable vegetation cover on mine tailings over the long-term that can lead to mine closure.

6.2 Germination and establishment

The results of this study emphasised that coated seed of *Eragrostis curvula* germinated faster than non-coated seed of the same species on slope plots for all trials undertaken. This species also produced a higher density and frequency over the two-year study. Non-coated seed of *E. curvula* germinated faster on some gold TSF flat plots, but overall, coated seed germinated faster and produced more sustainable populations throughout. *Eragrostis curvula* produced second-generation

viable seed and survived in plots without mulch after initial low densities and frequencies, indicating survival in the seedbed under adverse acidic conditions, as found in gold TSFs. Seed coating had a positive effect for this species and is therefore recommended for rehabilitation of gold mine TSFs. Furthermore, the fact that coated seed contained approximately 50% less seed per kilogram compared to non-coated seed proved that the coating worked well for this species.

Cynodon dactylon performed well once it had established after one year's growth. Initial germination percentages were comparable to the other species in the seed mix, although non-coated seed germinated with considerably higher percentages on both gold TSF trial sites. In the platinum TSF trials, *C. dactylon* coated seed germinated faster than non-coated seed. A decrease in population density was recorded during the first year, where *E. curvula* and *E. tef* dominated the space, due to the higher competition effect. When the competition effect was reduced in the second year, with less *E. tef* plants surviving, the growth of *C. dactylon* increased. *Cynodon dactylon* also survived in plots where no mulch was added, especially during the second growth season, and also established in areas where other species had not grown effectively. This species is therefore recommended as a successful rehabilitation species to be included in the seed mix, but at higher quantities per ha than were used during this study to limit the losses due to competition for space against other annual and perennial species. Regarding cost implications, the use of coated seed again was the best practical option.

Eragrostis tef was only used in the seed mix for one gold TSF trial due to the existing specification for the rehabilitation contractor, Agreenco Environmental Projects. Non-coated seed germinated fast and established very well. The recommendation is in line with current specifications, namely that lower quantities of *E. tef* should be sown, as this species can easily dominate a rehabilitation trial due to fast establishment and decrease the growth form of perennial species because of its high competition ability. This species is recommended to be included in the seed mixture for re-seeding rehabilitated areas in lower quantities, as it responded well, established well, grew fast and added to the plant biomass, which not only reduced dust pollution, but could also be harvested after the first season.

Coated seed of *Medicago sativa* germinated and established better on the flat TSFs surfaces. High percentages of germinated coated and non-coated seed were observed in the early stages of the trials, where this species played an important role in nitrogen fixation and to increase the soil stability. *Medicago sativa* established well on slope trials as well, although non-coated seed surpassed coated seed in certain trials. This species is perennial, but reports have stated that numbers decrease drastically if not harvested. This was observed in the trials as *M. sativa* almost disappeared during the second growth season. Seedbanks of this species often occur in topsoil, if used in the rehabilitation phase. If topsoil is not used, it is recommended to include *M. sativa* in the seed mixture for rehabilitating gold TSFs, but possibly in higher quantities per ha.

Sorghum sp. used in this study is annual forage sorghum. It was a good species to include in the seed mixture, especially when rehabilitating gold TSF material where mulch is added. Where no mulch was used, low percentages of sorghum established and did not survive in the second growth season due to its annual form. Some sorghum plants were observed during the second growth season as a result of the seedbank that was produced, which also indicates that this species can produce viable second generation seed, even though it is common in gold TSF material for some grass species to not produce viable seed from the parent plant. Sorghum played an important role in soil stability and decreasing wind pollution and damage to smaller grass species, because this species grows fast and produces a large canopy. Coated seed of forage sorghum performed better overall and it is recommended that this species forms part of the seed mixture for rehabilitation.

6.3 Soil amelioration

The study showed the importance of adequate soil amelioration specifications and when the amelioration is carried out. Lime requirements for gold TSFs were much higher than the equivalent agricultural requirement, but are critical to the successful establishment of vegetation as shown throughout this study. pH levels decreased approximately six months after amelioration and the soil analysis showed pH levels that are able to sustain vegetation, correct pH levels enable the production of viable seed and allows the uptake of plant critical nutrients. Results also showed that through the establishment of vegetation on TSFs, nutrient levels increased

(specifically micro- and macronutrients), although at low levels. This will guide the recommendation for additional coating of species for TSF rehabilitation.

6.4 General concluding remarks

Research by Goldberg (1990) and Gibson (2009) has shown that plant-to-plant interactions occur through the availability of natural resources and that emergence and growth of plants over time play a critical role in rehabilitation processes. Although opportunistic weed species occurred in the trial sites where compost and/or mulch was added, the impact thereof was of little consequence, especially over the long-term. In larger scale rehabilitation operations, caution should, however, be taken to see that not too many weeds and invasive species are included in the organic and/or mulch cover, as they may cause major problems through competition effects.

High viability of procured seed for rehabilitation efforts is crucial. Minimum accepted viability should be 80% and ideally higher if possible. The value of high viability was shown during this trial with very high germination percentages in unfavourable TSF soil conditions. The effect of the coating as buffer against low pH conditions was also found to be helpful as proposed by Westcott (2011). In very low rainfall seasons, coated seed could survive longer in anticipation of sufficient rainfall to penetrate the seed coating Westcott (2011). Coated seed may germinate faster when exposed to adequate rainfall conditions to allow the coating to dissolve, thereby increasing growth and longer term survival. Although non-coated seed used in this trial recovered to reach similar population densities as shown in Chapter 5 section 5.5.2, visual observation between coated and non-coated trials showed no difference in canopy cover after two growth seasons – confirming the importance of scientific field surveys.

6.5 Recommendations

The purpose of scientific research should be to test probabilities, to discover new pathways and to show the way for renewed ways of completing known tasks. As is always the case, every research subject creates the need for further research that will push the boundaries and ensure striving for improved performance. This is also

the case for successful long-term rehabilitation practices. The recommendations for further research include the following:

- The use of alternative species for rehabilitation such as winter cover crops. Industry is easily convinced that a certain species mix is the only possible outcome and omit trying new and innovative ways to improve on the available knowledge. The need exists for clear scope and ecological requirements prior to rehabilitation expectations and specifications. Clear scoping will assist in the determination of soil requirements, species availability as well as suitability and ensure sufficient time and budget requirements are met.
- Seasonal rains are a major driver behind successful rehabilitation efforts. Climate change will influence further research, the type of plant species currently used and possibilities for future use of certain species. Further innovative research is required to minimise the environmental impact of mine TSFs in a dryland setting. Project planning should also be completed early enough to allow sufficient time for vegetation establishment early in the growth season.
- Further research is required on the possibility of seed coating alterations to apply mineral/TSF-specific coating to individual species. Thereby creating “super” seed with a higher chance of long-term survival. This study indicated certain associations between seed species and nutrient levels – this can be used as a starting point to implement specific seed coatings.
- Field surveys are critical for the monitoring of successful establishment over time and remain a key component to scientific research. The recommendation is, however, that it must be combined in further research using unmanned aerial vehicle (i.e. drone) technology for monitoring stand establishment. By using normalised difference vegetation index capable software, comparisons and valuable data can be obtained to detect successful rehabilitation efforts but also areas prone to failure.
- Cares should be taken during rehabilitation efforts to implement high quality soil amelioration and soil sampling analysis, as these are critical when undertaking rehabilitation efforts and can decrease chances of success drastically if not undertaken correctly.

It is clear from this study that rehabilitation cannot re-create a 100% naturally rehabilitated and self sustaining post mining land use. This also creates industry-related concerns since closure is almost unobtainable and expensive, only to leave an area un-usable after years of rehabilitation.

The final recommendation is to apply the legislation for mine rehabilitation much more strictly and impose regulations for early rehabilitation efforts. As the rehabilitated TSFs can be regarded as novel ecosystems (also called emerging ecosystems) (Murcia *et al.*, 2014), these altered environments cannot be expected to be similar to the natural environment (Hobbs *et al.*, 2006). Therefore, new requirements and regulations should be created when it comes to the rehabilitation of TSFs, i.e. requirements and regulations that are more realistic and obtainable in terms of post-mining sustainable mining landscapes.

Chapter 7

References

ADVANCE SEED, s.a. AgriCOTE^{GT} pamphlet.

ADVANCE SEED. 2015. Advance Seed website. <http://www.advanceseed.com>.
Date of use: 17 October 2015.

Akcil, A. 2002. First application of cyanidation process in Turkish gold mining and its environmental impacts. *Minerals engineering*, 15(9):695-699.

Akcil, A. & Toldas, S. 2004. Acid mine drainage (AMD): causes, treatment and case studies. *Journal of cleaner production*, 14(12):1139-1145.

Anderson, D., Hamilton, L.P., Reynolds, H.G. & Humphrey, R.R. 1957. Reseeding desert grassland ranges in southern Arizona. Tucson, Ariz.: University of Arizona. College of Agriculture.

Australia, EPA Primer 2006. Environmental Protection Authority. Guidance for the Assessment of Environmental Factors. Rehabilitation of terrestrial ecosystems.

Ayres, R.U. 1997. Metals recycling: economic and environmental implications. *Resources, conservation and recycling*, 21(3):145-173.

Azapagic, A., 2004. Developing a framework for sustainable development indicators for the mining and minerals industry. *Journal of cleaner production*.

Barke, M.B. and Luebke, R.A., Cargill Incorporated, 1981. *Stable protective seed coating*. U.S. Patent 4,272,417.

Barnes, S.J. & Maier, W.D. 2002. Platinum-group element distributions in the Rustenburg layered suite of the Bushveld Complex, South Africa. (*In* Cabri, L.J.

The geology, geochemistry, mineralogy and mineral beneficiation of platinum-group elements. *Canadian Institute of Mining, Metallurgy and Petroleum*, 54:431-458.)

Beegle, D.B. 2001. Soil acidity and aglime. http://extension.psu.edu/plants/nutrient-management/educational/soil-fertility/soil-acidity-and-aglime/extension_publication_file Date of access: 5 June 2016.

Bell, D.T., Plummer, J.A. & Taylor, S.K. 1993. Seed germination ecology in South Western Australia. *Botanical review*, 59(1):24-73.

Bell, R.W., 2002. Restoration of degraded landscapes: Principles and lessons from case studies with salt-affected land and mine revegetation. *CMU. Journal*, 1(1), p.2.

Billiton BHP. 2009. Olympic dam expansion draft environmental impact statement. Appendix T: Rehabilitation and closure. London: Bhpbilliton.

Boshoff, J.C.J. & Hamman, J.N. 2011. Investigation into the current closure practices of platinum tailings storage facilities: the South African context. (Proceedings published by the Australian Centre for Geomechanics. Mine closure, nr. 1.)

Bothma, A. 2001. The rehabilitation of Impala no. 1A ventilation shaft. *Journal of South African Institute of Mining and Metallurgy*, 101(4):177-182.

Bradshaw, A. 1998. Restoration of mined lands: using natural processes. *Ecological engineering*, 8(4):255-269.

Brady, N.C. & Weil, R.R. 2008. An introduction to the nature and properties of soils. Upper Saddle River, N.J.: Prentice Hall.

Brits, Y. 2007. A comparison of selected enhanced (coated) and non-enhanced grass seed types for re-seeding of disturbed areas. Potchefstroom: North-West University. (Dissertation - MSc.)

Burgin, S. 2008. BioBanking: an environmental scientist's view of the role of biodiversity banking offsets in conservation. *Biodiversity and conservation*, 17(4):807-816.

Cairncross, B. 2006. History of the Okiep Copper district. Johannesburg: Rand Afrikaans University.

Cairncross, B. 2006. History of the Okiep Copper district. Rand Afrikaans University.

Cairns, J. 1995. Ecological integrity of aquatic systems. *Regulated rivers: research & management*, 11(3/4):313-323.

Carrick, P.J. and Krüger, R., 2007. Restoring degraded landscapes in lowland Namaqualand: Lessons from the mining experience and from regional ecological dynamics. *Journal of Arid Environments*, 70(4), pp.767-781.

Cobb, G.P., Sands, K., Waters, M., Wixson, B.G. & Dorward-King, E. 2000. Accumulation of heavy metals by vegetables grown in mine wastes. *Environmental toxicology and chemistry*, 19(3):600-607.

Cooke, J.A. & Johnson, M.S. 2002. Ecological restoration of land with particular reference to the mining of metals and industrial minerals: a review of theory and practice. *Environmental reviews*, 10(1):41-71.

Cramer, L.A. 2001. The extractive metallurgy of South Africa's platinum ores. *JOM*, 53(10):14-8.

Darkoh, M.B.K. 1998. The nature, causes and consequences of desertification in the drylands of Africa. *Land degradation & development*, 9(1):1-20.

Davies, T.C. & Mundalamo, H.R. 2010. Environmental health impacts of dispersed mineralisation in South Africa. *Journal of African earth sciences*, 58(4):652-666.

De Groot, R.S., Wilson, M.A. & Boumans, R.M. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological economics*, 41(3):393-408.

Deaker, R., Roughley, R.J. & Kennedy, I.R. 2007. Desiccation tolerance of rhizobia when protected by synthetic polymers. *Soil biology and biochemistry*, 39(2):573-580.

Doran, J.W. & Zeiss, M.R. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Applied soil ecology*, 15(1):3-11.

ELD (Economics of Land Degradation). 2015. The value of land: prosperous lands and positive rewards through sustainable land management. <http://www.eld-initiative.org> Date of access: 15 April 2016.

ELD Initiative. 2013. The rewards of investing in sustainable land management. Interim Report for the Economics of Land Degradation Initiative: a global strategy for sustainable land management. <http://www.eld-initiative.org> Date of access: 15 April 2016.

Environmental Protection Authority. 2006. Guidance for the assessment of environmental factors: rehabilitation of terrestrial ecosystems. Perth: Western Australia. (Environmental Protection Authority Western Australia, nr. 6.)

Fourie, A. & Brent, A.C. 2006. A project-based mine closure model (MCM) for sustainable asset life cycle management. *Journal of cleaner production*, 14(12):1085-1095.

Franks, D.M., Boger, D.V., Côte, C.M. and Mulligan, D.R., 2011. Sustainable development principles for the disposal of mining and mineral processing wastes. *Resources policy*, 36(2), pp.114-122.

FSSA (Fertilizer Society of South Africa). 2007. Fertilizer handbook. 6th rev. ed. Lynnwood Ridge, SA: Fertilizer Society of South Africa.

Ghose, M. 2001. Management of topsoil for geo-environmental reclamation of coal mining areas. *Environmental geology*, 40(11/12):1405-1410.

Gibbons, P. & Lindenmayer, D.B. 2007. Offsets for land clearing: no net loss or the tail wagging the dog. *Ecological management & restoration*, 8(1):26-31.

Gibson, D.J. 2014. *Methods in comparative plant population ecology*. Oxford: Oxford University Press.

Goldberg, D.E. 1990. Components of resource competition in plant communities. (In Grace, J.B. & Tilman, J., eds. *Perspectives on plant competition*. New York: Academic Press. p. 27-49.)

González, R.C. & González-Chávez, M.C. 2006. Metal accumulation in wild plants surrounding mining wastes. *Environmental pollution*, 144(1):84-92.

Goulding, K.W.T. & Blake, L. 1998. Land use, liming and the mobilization of potentially toxic metals. *Agriculture, ecosystems & environment*, 67(2):135-144.

Haagner, A.S.H. 2008. The role of vegetation in characterising landscape function on rehabilitating gold tailings. Potchefstroom: North-West University. (Thesis - PhD.)

Handley, J.R.F. 1990. World gold resources: a review at the end of the 1980 decade. Johannesburg: University of the Witwatersrand. (Information circular University of the Witwatersrand. Economic Geology Research Unit, no. 227.)

Hartzer, S. 2009. The liability of historical mine authorization holders for rehabilitation. North-West University, Potchefstroom. (LLM Environmental Law and governance).

Hattingh, R.P. 2001. Guidance for the rehabilitation of contaminated gold tailings dams footprints. Pretoria: Water Research Commission. (WRC Report No 1001/2/03.)

- Herrick, J.E. 2000. Soil quality: an indicator of sustainable land management? *Applied soil ecology*, 15(1):75-83.
- Hilson, G. 2000. Pollution prevention and cleaner production in the mining industry: an analysis of current issues. *Journal of cleaner production*, 8(2):119-126.
- Hilson, G. & Monhemius, A.J. 2006. Alternatives to cyanide in the gold mining industry: what prospects for the future? *Journal of cleaner production*, 14(12):1158-1167.
- Hobbs, R.J. & Harris, J.A. 2001. Restoration ecology: repairing the earth's ecosystems in the new millennium. *Restoration ecology*, 9(2):239-246.
- Hobbs, R.J., Arico, S., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V.A., Epstein, P.R., Ewel, J.J., Klink, C.A., Lugo, A.E., Norton, D., Ojima, D., Richardson, D.M., Sanderson, E.W., Valladares, F., Vilà, M., Zamora, R. & Zobel, M. 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global ecology and biogeography*, 15(1):1-7.
- Huang, J., Chen, J., Berti, W.R. & Cunningham, S.D. 1997. Phytoremediation of lead-contaminated soils: role of synthetic chelates in lead phytoextraction. *Environmental science & technology*, 31(3):800-805.
- Huggett, R.J. 1998. Soil chronosequences, soil development, and soil evolution: a critical review. *Catena*, 32(3):155-172.
- Horneck, D.A., Sullivan, D.M., Owen, J.S. and Hart, J.M., 2011. *Soil test interpretation guide*. [Corvallis, Or.]: Oregon State University, Extension Service.
- ISTA, 2006. International Rules For Seed Testing. 2006 Ed. International Seed Testing Association. ISTA. Basserdorf. CA-Switzerland. Chapters 2, 5 & 11.
- Jim, C.Y., 2001. Ecological and landscape rehabilitation of a quarry site in Hong Kong. *Restoration Ecology*, 9(1), pp.85-94.

- Johnson, M.S. & Bradshaw, A.D. 1977. Prevention of heavy metal pollution from mine wastes by vegetative stabilization. *Transactions Institute of Mining and Metallurgy*, 86:A47-A55.
- Kalin, M. & Harris, B. 2005. Chemical precipitation within pyritic waste rock. *Hydrometallurgy*, 78(3):209-225.
- Kalin, M., Fyson, A. and Wheeler, W.N. 2006. The chemistry of conventional and alternative treatment systems for the neutralization of acid mine drainage. *Science of the Total Environment*, 366(2), pp.395-408.
- Kaufman, G., 1991. Seed coating: a tool for stand establishment; a stimulus to seed quality. *HortTechnology*, 1(1):98-102.
- Kent, M. 2011. Vegetation description and data analysis, a practical approach. 2nd ed. Hoboken, N.J.: Wiley.
- Kettle, A.J., Gedye, C.A., Hampton, M.B. & Winterbourn, C.C. 1995. Inhibition of myeloperoxidase by benzoic acid hydrazides. *Biochemical journal*, 308(2):559-563.
- Khan, A.G. 2005. Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. *Journal of trace elements in medicine and biology*, 18(4):335-364.
- Khan, A.G., Kuek, C., Chaudhry, T.M., Khoo, C.S. & Hayes, W.J. 2000. Role of plants, mycorrhizae and phytochelators in heavy metal contaminated land remediation. *Chemosphere*, 41(1):197-207.
- Kundu, N.K. & Ghose, M.K. 1994. Studies on, the topsoil of an underground coal-mining project. *Environmental conservation*, 21(2):126-132.
- Laubscher, P.J., Eloff, F.C., Van Aarde, M.N., Du Plessis, J.L., Franken, A. & Griesel, H. 2009. Characterisation of and exposure of workers to tailings dust at South African platinum mines. *Journal of the Mine Ventilation Society of South Africa*, 62(1):16-20.

Laurence, D. 2011. Establishing a sustainable mining operation: an overview. *Journal of Cleaner Production*, 19(2):278-284.

Laurence, D. 2006. Optimisation of the mine closure process. *Journal of cleaner production*, 14(3):285-298.

Logsdon, M.J., Hagelstein, K. & Mudder, T.I. 1999. The management of cyanide in gold extraction. Ottawa: International Council on Metals and the Environment.

Loyd, P.J. 1994. Environmental protection in South Africa. *Journal of the South African Institute of Mining and Metallurgy*, 94(6):111-118.

Lubke, R.A. and Avis, A.M., 1999. A review of the concepts and application of rehabilitation following heavy mineral dune mining. *Marine Pollution Bulletin*, 37(8):546-557.

Maboeta, M.S. & Van Rensburg, L. 2003. Bioconversion of sewage sludge and industrially produced woodchips. *Water, air, and soil pollution*, 150(1/4):219-233.

Manzi, T., Lucas, K., Lloyd-Jones, T. & Allen, J. 2010. Understanding social sustainability: key concepts and developments in theory and practice. (In Manzi, T., Lucas, K., Lloyd-Jones, T. & Allen, J. Social sustainability in urban areas, communities, connectivity and the urban fabric. London: Earthscan. p. 1-28.)

Maseki, J. 2013. Land use, liming and the mobilization of potentially toxic metals. Johannesburg: University of Johannesburg. (Dissertation - MSc.)

Mchaina, D.M. 2001. Environmental planning considerations for the decommissioning, closure and reclamation of a mine site. *International Journal of Surface Mining, Reclamation and Environment*, 15(3):163-176.

Mendez, M.O. & Maier, R.M. 2008. Phytostabilization of mine tailings in arid and semi-arid environments: an emerging remediation technology. *Environmental health perspectives*, 116(3):278-283.

Mendez, M.O., Glenn, E.P. & Maier, R.M. 2007. Phytostabilization potential of quailbush for mine tailings. *Journal of environmental quality*, 36(1):245-253.

Miller, R.M. & Jastrow, J.D. 1992. The role of mycorrhizal fungi in soil conservation. (In Bethlenfalvay, G.J. & Lindemans, R., eds. *Mycorrhizae in sustainable agriculture*. American Society of Agronomy. Madison, Wis.: American Society of Agronomy. p. 29-44. (Special publication no. 54.))

Mohr-Swart, M. & Tanner, P. 2007. Guidelines for the rehabilitation of mined land. Johannesburg: Chamber of Mines of South Africa/Coaltech 2020.

Mphephu, N.F. 2005. Rehabilitation of Tailings Dams on the Central Rand. Johannesburg: University of the Witwatersrand. Centre for Applied Mining and Exploration Geology.

Mucina, L. & Rutherford, M.C., eds. 2006. The vegetation of South Africa, Lesoto and Swaziland. Pretoria: South African National Biodiversity Institute. (Memoirs of the Botanical Survey of South Africa, Stelitzia 19.)

Muller, I. 2014. Effects of seed coating on the germination of selected grass species in different mine tailings deposits: a nursery trial. Potchefstroom: North-West University, Potchefstroom. (Dissertation - M.Sc.).

Mulligan, C.N., Yong, R.N. & Gibbs, B.F. 2001. Remediation technologies for metal-contaminated soils and groundwater: an evaluation. *Engineering geology*, 60(1):193-207.

Munshower, F.F. 1994. Practical handbook of disturbed land revegetation. Boca Raton, Fla.: Lewis.

Murcia, C., Aronson, J., Kattan, G.H., Moreno-Mateos, D., Dixon, K. & Simberloff, D., 2014. A critique of the 'novel ecosystem' concept. *Trends in ecology & evolution*, 29(10):548-553.

Nel, L. 2013. The role of seed coating in the establishment and growth of *Medicago sativa* L. cultivars. Pretoria: University of Pretoria. (Dissertation - MSc.)

Ngcofe, L. & Cole, D.I. 2014. The distribution of the economic mineral resource potential in the Western Cape Province. *South African journal of science*, 110(1/2):1-4.

OED (Oxford English Dictionary). 2010. Topsoil. Oxford: At the Clarendon Press.

Orlekowsky, T., Venter, A., Van Wyk, F. & Levanets, A. 2013. Cyanobacteria and algae of gold mine tailings in the Northwest Province of South Africa. *Nova Hedwii*, 97(3/4):281-294.

Radić, V., Vujaković, M. & Marjanović-Jeromela, A. 2007. Influence of drought on seedling development in different corn genotypes (*Zea mays* L.). *Journal of agricultural sciences*, 52(2):131-136.

Raskin, I. & Ensley, B.D. 2000. Phytoremediation of toxic metals using plants to clean up the environment. New York: Wiley.

Read, T.R., Bellairs, S.M., Mulligan, D.R. & Lamb, D. 2000. Smoke and heat effects on soil seed bank germination for the re-establishment of a native forest community in New South Wales. *Austral ecology*, 25(1):48-57.

Reichardt, M.A. 2012. History of mine wastes rehabilitation techniques in South Africa: a multi-disciplinary overview of mine waste rehabilitation and the non-scientific drivers for its implementation 1950s - 1980s. Johannesburg: University of the Witwatersrand. (Thesis - PhD.)

Robb, L.J. & Meyer, F.M. 1995. The Witwatersrand Basin, South Africa: geological framework and mineralization processes. *Ore geology reviews*, 10(2):67-94.

Römheld, V. and Kirkby, E.A. 2010. Research on potassium in agriculture: needs and prospects. *Plant and Soil*, 335(1-2):155-180.

Rossouw, A.S., Furniss, D.G., Annegarn, H.J., Weiersbye, I.M., Ndolo, U. and Cooper, M. 2009. Evaluation of a 20–40 year old gold mine tailings rehabilitation project on the Witwatersrand, South Africa.

Ruiz-Jaen, M.C. & Mitchell Aide, T. 2005. Restoration success: how is it being measured? *Restoration ecology*, 13(3):569-577.

Schoeman, J.L. & Van Deventer, P.W. 2004. Soils and the environment: the past 25 years. *South African journal of plant and soil*, 21(5):369-387.

Schwartz, D. & Singh, A. 1999. Environmental conditions, resources, and conflicts: An introductory overview and data collection. Sioux Falls, S.D.: United Nations Environment Programme.

Schwartz, M.W., Brigham, C.A., Hoeksema, J.D., Lyons, K.G., Mills, M.H. & Van Mantgem, P.J. 2000. Linking biodiversity to ecosystem function: implications for conservation ecology. *Oecologia*, 122(3):297-305.

Scott, J.M. 1989. Seed coatings and treatments and their effects on plant establishment. *Advances in agronomy*, 42:43-83.

SER (Society for Ecological Restoration). 2004. Society for Ecological Restoration: primer. Washington, D.C.: SER.

Sharitz, R.R. and McCormick, J.F. 1973. Population dynamics of two competing annual plant species. *Ecology*, 54(4):723-740.

South Africa. 1976. Plant Improvement Act, No 53 of 1976. Table 4 amended, corrected and substituted by R928 of 30 September 2005. Provision Relating to Seed and Seed Samples. Pretoria: Government Printer.

South Africa. 1979. Guidelines for environmental protection. Pretoria: Government Printer. Pretoria: Government Printer.

South Africa. 1983. Conservation of Agricultural Resources Act 43 of 1983. Pretoria: Government Printer.

South Africa. 1996. Constitution of South Africa, Act 108 of 1996. Pretoria: Government Printer.

South Africa. 1998a. National Environmental Management Act 107 of 1998. Pretoria: Government Printer.

South Africa. 1998b. National Water Act 36 of 1998. Pretoria: Government Printer.

South Africa. 2002. Mineral and Petroleum Resources Development Act 2002. Pretoria: Government Printer.

South Africa. 2004a. National Environmental Management Air Quality Act 39 of 2004. Pretoria: Government Printer.

South Africa. 2004b. National Environmental Management Biodiversity Act 10 of 2004. Pretoria: Government Printer.

South Africa. 2008. National Environmental Management Waste Act 59 of 2008. Pretoria: Government Printer.

Spitz, K. & Trudinger, J. 2009. Mining and the environment: from ore to metal. Boca Raton, Fla.: CRC Press.

Suryaningtyas, D.T. & Gautama, R.S. 2008. Acid mine drainage treatment of overburden for the removal of Cation Metals. Barat, Indonesia: Bogor Agricultural University. Department of Soil Science and Land Resources.

Sutton, M.W. & Weiersbye, I.M. 2008. Land-Use after mine closure: risk assessment of gold and uranium mine residue deposits on the Eastern Witwatersrand, South Africa. Johannesburg: University of the Witwatersrand.

Swart, E. 2003. The South African legislative framework for mine closure. *Journal-South African Institute of Mining and Metallurgy*, 103(8):489-492.

Tarras-Wahlberg, N.H., Flachier, A., Lane, S.N. and Sangfors, O. 2001. Environmental impacts and metal exposure of aquatic ecosystems in rivers contaminated by small scale gold mining: the Puyango River basin, Southern Ecuador. *Science of the Total Environment*, 278(1):239-261.

Taylor, A.G. and Harman, G.E., 1990. Concepts and technologies of selected seed treatments. *Annual review of phytopathology*, 28(1):321-339.

Ter Braak, C.J. 1988. Canoco-a FORTRAN program for canonical community ordination by [partial] [detrended] [canonical] correspondence analysis, principal components analysis and redundancy analysis (version 2.1). Wageningen: GLW. Technical report / Ministerie van Landbouw en Visserij. Groep Landbouwwiskunde, LWA-88-02.

Tongway, D.J. & Hindley, N.L. 2004. Landscape function analysis: procedures for monitoring and assessing landscapes with special reference to minesites and rangelands. Canberra, ACT: CSIRO Sustainable Ecosystems.

Tongway, D.J. & Murphy, D. 1999. Principles for designed landscapes and monitoring of ecosystem development in rangelands affected by mining. (Proceedings of the 6th International Rangeland Congress. People and Rangelands: Building the Future. p. 945-949.)

Tordoff, G.M., Baker, A.J.M. & Willis, A.J., 2000. Current approaches to the revegetation and reclamation of metalliferous mine wastes. *Chemosphere*, 41(1):219-228.

Török, P., Vida, E., Deák, B., Lengyel, S. and Tóthmérész, B. 2011. Grassland restoration on former croplands in Europe: an assessment of applicability of techniques and costs. *Biodiversity and Conservation*, 20(11):2311-2332.

Turner, S.R., Pearce, B., Rokich, D.P., Dunn, R.R., Merritt, D.J., Majer, J.D. & Dixon, K.W. 2006. Influence of polymer seed coatings, soil raking, and time of sowing on seedling performance in post-mining restoration. *Restoration ecology*, 14(2):267-277.

United States Environmental Protection Agency. 1994. Technical report: design and evaluation of tailings dams. Washington, D.C.

Van den Bergh, L. & Kellner, K. 2005. Restoring degraded patches in semi-arid rangelands of South Africa. *Journal of arid environments*, 61(3):497-511.

Van den Bergh, L. & Kellner, K. 2010. Important factors for ecotype selection in restoration application. *South African journal for natural science and technology*, 29(4):185-195.

Van Deventer, P.W. 2002. Rehabilitation of tailings dams: rock-cladding in perspective. <http://www.envirogreen.co.za/rock.htm> Date of access: 16 April 2016.

Van Oudtshoorn, F. 2006. Grasses of South Africa. 2nd ed. Pretoria: Briza Publications.

Van Wyk, S.J. 2002. An analytical investigation of the biophysical factors that inhibit successful ecological restoration of gold tailings dams. Potchefstroom: Potchefstroom University for Christian Higher Education. (Dissertation - MSc.)

Viljoen, M.J. & Reimold, W.U. 2002. An introduction to South Africa's geological and mining heritage. Randburg: Geological Society.

Weiersbye, I.M. 2007. Global review and cost comparison of conventional and phytotechnologies for mine closure. (In Fourie, A.B., Tibbett M. & Wiertz, J., eds. Mine closure 2007. Plenary paper in the Proceedings of the 2nd International Seminar on Mine Closure. p. 13-19.)

Weiersbye, I.M. & Witkowski, T.F. 2007. Impacts of acid mine drainage on the regeneration of Highveld Phreatophytes. (In Seydack, A.H.W., Vorster, T.,

Vermeulen, W.J. & Van der Merwe, I.J., eds. Multiple use management of natural forests and woodlands: policy refinements and scientific progress IV. Pretoria: Department of Water Affairs and Forestry. p. 224-237.)

Weiersbye, I.M., Straker, C.J. & Przybylowicz, W.J. 1999. Micro-PIXE mapping of elemental distribution in arbuscular mycorrhizal roots of the grass, *Cynodon dactylon*, from gold and uranium mine tailings. *Nuclear instruments and methods in physics research, Section B: Beam interactions with materials and atoms*, 158(1):335-343.

Westcott, M. 2011. An evaluation of the germination and establishment of three selected coated grass species in different soil types for rehabilitation. Potchefstroom: North-West University. (Dissertation - MSc.)

Westoby, M., Falster, D.S., Moles, A.T., Vesk, P.A. and Wright, I.J. 2002. Plant ecological strategies: some leading dimensions of variation between species. *Annual review of ecology and systematics*, pp.125-159.

Wilson, M.J. & Bell, N. 1996. Acid deposition and heavy metal mobilization. *Applied geochemistry*, 11(1):133-137.

Wong, M.H. 2002. Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. *Chemosphere*, 50(6):775-780.

Worrall, R., Neil D., Brereton, D. & Mulligan, D. 2009. Towards a sustainability criteria and indicators framework for legacy mine land. *Journal of cleaner production*, 17(16):1426-1434.

Anonymous. <http://www.worlweatheronline.com>. Web source. Date of access: 12 June 2016.

Zhao, B., Usher, B.H., Yibas, B. & Pulles, W. 2010. Evaluation and validation of geochemical prediction techniques for underground coal mines in the Witbank/Vryheid regions. Bloemfontein: University of the Free State. Institute for groundwater studies. (Research Report No.1249/1/10.)

Zingel, M., Froneman, P & Bruwer, B. 2007. General knowledge of the seed industry: a Unit Standard for the Seed Industry, standard 114670. Pretoria: SANSOR.

Appendix A

Soil sample analysis reports, as received from the laboratories of EcoAnalytica.

Appendix A1 – Table of sample identification.

1	Crown slope Coated	2015
2	Crown slope Non-coated	2015
3	Crown flat Coated	2015
4	Crown flat Non Coated	2015
5	Rooikraal slope Coated	2015
6	Rooikraal slope Non coated	2015
7	Rooikraal flat Coated	2015
8	Rooikraal flat Non-coated	2015
9	Crown slope Coated	Aug2016
10	Crown slope Non-coated	Aug2016
11	Crown flat Coated	Aug2016
12	Crown flat Non coated	Aug2016
13	Rooikraal slope Coated	Aug2016
14	Rooikraal slope Non coated	Aug2016
15	Rooikraal flat Coated	Aug2016
16	Rooikraal flat Non-coated	Aug2016
17	Paardekraal slope Coated	2015
18	Paardekraal slope Non-coated	2015

Appendix A2: Table of Nutrient status of the trial locations

10/10/2016		Voedingstatus								
Monster	Ca	Mg	K	Na	P	pH(H ₂ O)	pH(KCl)	EG	Olsen P	
no.			(mg/kg)					(mS/m)	mg/kg	
1	1823.5	23.5	36.5	9.5	7.1	3.60	3.61	265	3.2	
2	1526.0	1.0	31.5	8.5	4.5	3.66	3.63	231	3.1	
3	2891.0	188.5	34.0	7.0	4.2	3.39	3.41	386	3.1	
4	2124.5	120.0	43.5	5.0	4.0	3.39	3.42	390	3.0	
5	829.5	54.0	33.5	4.0	5.2	3.64	3.76	240	3.4	
6	541.5	1.0	42.0	13.5	6.1	5.30	4.05	224	3.7	
7	373.0	1.0	40.0	10.0	5.6	5.08	4.72	176	4.4	
8	739.0	1.0	43.5	9.5	3.9	4.04	3.88	220	3.7	
9	685.5	235.5	76.0	53.0	12.0	7.01	7.22	181	6.6	
10	2113.5	269.5	93.5	18.5	18.3	7.68	8.32	137	10.8	
11	1736.5	115.5	56.5	15.0	13.8	6.29	6.09	251	6.2	
12	2083.5	552.5	66.5	65.0	8.5	6.43	6.31	475	4.8	
13	717.0	49.5	58.0	11.0	49.2	4.49	4.58	230	9.6	
14	600.0	78.0	60.0	13.0	77.2	4.29	4.36	218	8.4	
15	369.5	58.5	52.5	10.0	38.9	6.38	6.39	50	10.5	
16	740.0	82.0	66.0	21.5	67.7	7.15	7.00	70	24.6	
17	679.0	25.5	43.5	25.0	7.9	7.16	7.49	145	7.2	
18	847.0	26.5	54.0	20.5	5.3	7.16	8.40	180	4.5	

Appendix A3: Table of particle size distribution of the trial locations.

10/10/201		Deeltjegrootteverspreiding		
Monster	> 2mm	Sand	Slik	Klei
		(% < as 2mm)		
PT1	0.0	85.2	11.9	2.9
PT2	0.0	85.8	11.5	2.8
PT3	0.0	79.4	15.0	5.6
PT4	0.0	72.6	21.5	5.9
PT5	0.0	88.3	9.0	2.7
PT6	0.0	93.1	4.2	2.6
PT7	0.0	95.5	2.0	2.6
PT8	0.0	95.4	4.2	0.4
PT17	0.0	88.1	11.5	0.4
PT18	0.0	90.7	8.9	0.4

Appendix A4: Table of exchangeable cations of the trial locations.

Uitruilbare katione									
Monster	Ca	Mg	K	Na	KUK	S-waarde	Basis versa-	pH(H ₂ O)	pH(KCl)
no.	(cmol(+)/kg)						diging (%)		
1	9.10	0.19	0.09	0.04	8.85	9.43	106.50	3.60	3.61
2	7.61	0.01	0.08	0.04	10.77	7.74	71.90	3.66	3.63
3	14.43	1.55	0.09	0.03	13.37	16.10	120.35	3.39	3.41
4	10.60	0.99	0.11	0.02	12.52	11.72	93.62	3.39	3.42
5	4.14	0.44	0.09	0.02	14.81	4.69	31.65	3.64	3.76
6	2.70	0.01	0.11	0.06	11.69	2.88	24.61	5.30	4.05
7	1.86	0.01	0.10	0.04	8.85	2.02	22.77	5.08	4.72
8	3.69	0.01	0.11	0.04	9.47	3.85	40.64	4.04	3.88
9	3.42	1.94	0.19	0.23	5.67	5.78	102.02	7.01	7.22
10	10.55	2.22	0.24	0.08	11.10	13.08	117.83	7.68	8.32
11	8.67	0.95	0.14	0.07	11.11	9.83	88.42	6.29	6.09
12	10.40	4.55	0.17	0.28	15.66	15.40	98.32	6.43	6.31
13	3.58	0.41	0.15	0.05	6.81	4.18	61.42	4.49	4.58
14	2.99	0.64	0.15	0.06	6.85	3.85	56.13	4.29	4.36
15	1.84	0.48	0.13	0.04	4.37	2.50	57.23	6.38	6.39
16	3.69	0.67	0.17	0.09	4.55	4.63	101.81	7.15	7.00
17	3.39	0.21	0.11	0.11	3.75	3.82	101.88	7.16	7.49
18	4.23	0.22	0.14	0.09	4.64	4.67	100.62	7.16	8.40

Appendix A5: Table of Macro nutrients of the trial locations.

1:2 EKSTRAK										
Makro-elemente										
Monster	Ca	Mg	K	Na	PO ₄	SO ₄	NO ₃	NH ₄	Cl	HCO ₃
nommer	<i>Millimol per liter</i>									
1	10.12	3.06	0.17	0.32	<0.01	13.44	0.27	0.28	0.12	0.00
2	10.98	1.10	0.13	0.18	<0.01	12.17	0.17	0.15	0.06	0.00
3	10.58	7.17	0.09	0.08	<0.01	18.72	0.17	0.02	0.13	0.00
4	10.77	6.43	0.01	0.01	<0.01	18.04	0.26	0.02	0.11	0.00
5	11.13	1.56	0.01	0.06	<0.01	12.77	0.19	0.11	0.08	0.00
6	10.05	2.16	0.75	1.21	<0.01	12.91	0.17	0.65	0.99	0.15
7	6.90	0.67	0.09	0.10	<0.01	7.67	0.13	0.25	0.07	0.10
8	14.72	0.47	0.08	0.10	<0.01	15.26	0.21	0.13	0.04	0.00
9	11.12	9.58	1.17	3.34	<0.01	21.54	0.09	0.00	1.95	0.95
10	6.11	3.48	0.71	0.29	<0.01	9.41	0.10	0.00	0.27	1.10
11	12.56	2.95	0.06	0.18	<0.01	15.35	0.22	0.01	0.17	0.20
12	12.13	13.91	0.25	3.01	0.03	26.77	0.59	0.03	1.20	0.30
13	10.04	2.64	0.27	0.11	<0.01	12.97	0.16	0.12	0.11	0.00
14	8.77	2.77	0.55	0.26	<0.01	11.95	0.16	0.07	0.12	0.00
15	1.75	0.37	0.02	0.10	<0.01	1.97	0.01	0.02	0.06	0.40
16	3.19	1.06	0.46	0.22	<0.01	3.91	0.02	0.02	0.08	1.30
17	4.49	0.25	0.18	0.51	<0.01	4.40	0.23	0.02	0.39	0.75
18	5.81	0.17	0.24	0.65	<0.01	5.72	0.17	0.02	0.48	0.85

Appendix A6: Table of Micro nutrients of the trial locations.

Mikro-elemente en ander data								
Monster	Fe	Mn	Cu	Zn	B	pH	EG	P-BRAY 1
nommer	Mikromol per liter						(mS/cm)	dpm
1	14.58	77.17	4.44	10.49	1	3.55	2.73	7.14
2	9.65	32.10	3.99	2.46	1	3.62	2.46	4.5
3	519.30	456.52	48.47	55.08	3	3.07	3.77	4.16
4	322.30	474.54	45.09	72.13	4	3.32	3.64	4.01
5	33.45	69.79	6.79	19.23	2	3.68	2.57	5.16
6	5.07	26.37	0.01	0.39	1	6.50	2.72	6.05
7	5.09	14.04	0.02	0.55	1	4.62	1.56	5.55
8	4.16	18.01	0.03	0.71	1	4.05	3.07	3.86
9	4.56	2.20	0.03	0.24	11	7.00	4.59	12
10	1.84	0.30	0.03	0.15	11	7.07	2.02	18.31
11	2.84	32.10	0.03	0.56	6	6.39	3.13	13.78
12	3.11	223.83	0.17	0.81	5	6.83	5.57	8.53
13	3.55	87.00	1.33	25.45	1	4.31	2.61	49.18
14	4.29	82.90	1.75	27.18	1	4.14	2.41	77.17
15	0.91	2.75	0.01	0.25	4	6.72	0.44	38.86
16	2.88	2.32	0.04	0.15	14	7.28	0.92	67.7
17	2.26	0.22	0.02	0.21	1	7.16	1.02	7.93
18	0.03	0.92	0.04	0.20	3	7.41	1.29	5.33

Appendix A7: Table of Macro nutrients – saturated paste of the trial locations.

SATURATED PASTE										
Makro-elemente										
Monster	Ca	Mg	K	Na	PO ₄	SO ₄	NO ₃	NH ₄	Cl	HCO ₃
nommer	Millimol per liter									
1					<0.01	2137.26	14.67		4.91	
2					<0.01	1755.71	7.76		1.35	
3					<0.01	4775.23	11.03		9.59	
4					<0.01	6205.40	11.25		8.35	
5					<0.01	1908.07	7.64		2.41	
6					<0.01	1628.82	16.77		2.58	
7					<0.01	1325.51	4.26		1.51	
8					<0.01	1532.68	16.17		1.27	
9					<0.01	1291.04	10.47		22.10	
10					<0.01	838.23	5.56		3.41	
11					<0.01	2026.09	11.55		4.11	
12					0.01	4876.22	37.60		36.78	
13					0.02	1781.64	12.90		1.99	
14					0.03	1566.80	15.35		1.83	
15					0.02	221.30	0.94		1.34	
16					0.01	291.13	1.95		1.66	
17					<0.01	913.90	17.67		20.18	
18					<0.01	1349.16	8.77		15.28	

Appendix B

Seed viability reports of trial species as received from AGT Foods Africa (Pty) Ltd.



SEED TEST LABORATORY
 AGT Foods Africa (Pty) Ltd
 PO Box 414, Krugersdorp 1740
 Tel: +2711-762 5261
 Fax: +2711-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)
 Reg. No. 1994/001269/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Teff SA Brown
 Botanical Name: Eragrostis tef
 Date sample received: 2016-03-10
 Weight of submitted sample (gram):1713gram

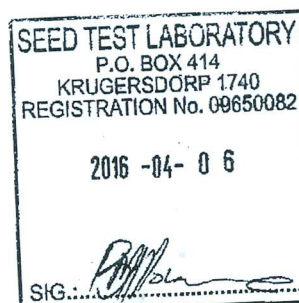
Code Number: 744
 Reference Number: A359/15

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-99.4-	-0.4-	-0.2-	-0.6-	10	-85-	-0-	-0-	-2-	-13-

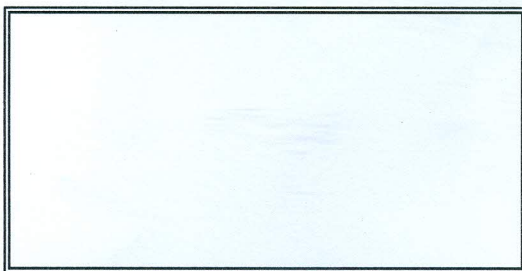
Inert matter: Broken caryopsis, soil
 Weed: (4) Cyperus sp. (3) Amaranthus sp.

Germination method: TP: 20<=>30°C :KNO₃

Remarks:



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
PO Box 414, Krugersdorp 1740
Tel: 011-762 5261
Fax: 011-762 4111

as registered with the National Department of
Agriculture's ISTA Accredited Seed Testing
Station in terms of the Plant Improvement Act,
1976 (Act 53 of 1976)

Reg. No. 94/01260/07
DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Cynodon
Botanical Name: Cynodon dactylon
Date sample received: 2015/10/22
Weight of submitted sample(gram) 1264.0gr

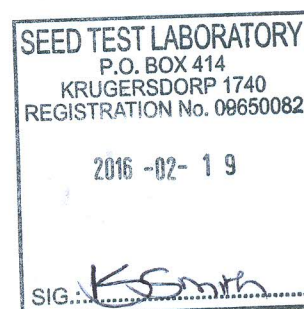
Code Number: 802
Reference Number: A708/15

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-98.8-	-1.2-	-0.0-	-1.2-	21	-79-	-0-	-0-	-7-	-14-

Inert matter: Broken seed, plant material

Germination method: TP:20<=>30°C

Remarks:



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Cynodon
 Botanical Name: Cynodon dactylon
 Date sample received: 2015/10/26
 Weight of submitted sample(gram) 785.0gr

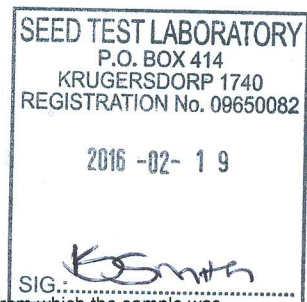
Code Number: 802E
 Reference Number: 221015

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
X	X	X	X	21	-75-	-0-	-0-	-7-	-18-

Inert matter:

Germination method: TP:20<=>30°C

Remarks: COATED SEED



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Smuts digitaria Irene
Botanical Name: Digitaria eriantha
Date sample received: 2016/02/11
Weight of submitted sample(gram) 454.3gr

Code Number: 873
Reference Number: A121/16

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-96.5-	-3.0-	-0.5-	-3.5-	14	-22-	-0-	-0-	-1-	-77-

Inert matter: Broken seed, plant material, stalks, sand

Weed: 0.5% 6 x Sporobolus sp. 5 x Urochloa sp. 6 x Verbena officinalis

Germination method: TP:20<=>30°C

Remarks:

SEED TEST LABORATORY
 P.O. BOX 414
 KRUGERSDORP 1740
 REGISTRATION No. 09650082

2016 -02- 23

SIG.: *K Smith*

Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Smuts digitaria Irene
Botanical Name: Digitaria eriantha
Date sample received: 2016/02/10
Weight of submitted sample(gram) 540.6gr

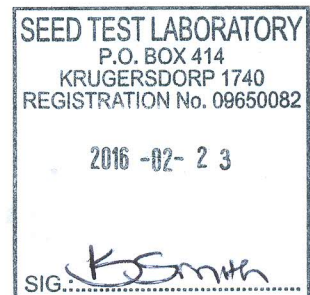
Code Number: 873E
Reference Number: 030216

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-X-	-X-	-X-	-X-	14	-22-	-0-	-0-	-1-	-77-

Inert matter:

Germination method: TP:20<=>30°C

Remarks: COATED SEED



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Forage Sorghum Supergraze
Botanical Name: Sorghum spp.
Date sample received: 2016-02-12
Weight of submitted sample (gram) 1465 gram

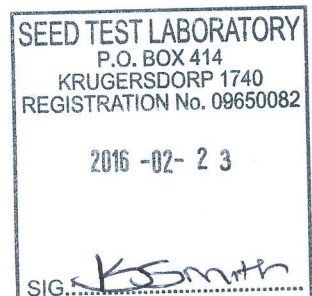
Code Number: 787/32
Reference Number: A156/16

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-99.9-	-0.1-	-0.0-	-0.1-	10	-88-	-0-	-0-	-7-	-5-

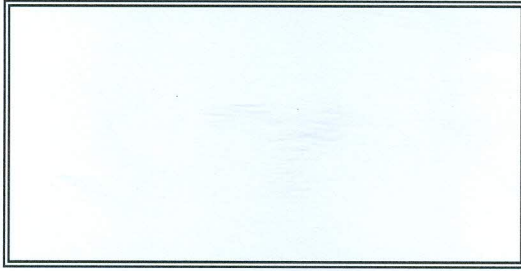
Inert matter: Broken seed

Germination method: BP:20<=>30°C

Remarks:



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the **National Department of Agriculture's ISTA Accredited Seed Testing Station** in terms of the Plant Improvement Act, 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Lucerne Supercuf
Botanical Name: Medicago sativa
Date sample received: 2016/02/16
Weight of submitted sample (gram) 1136gr

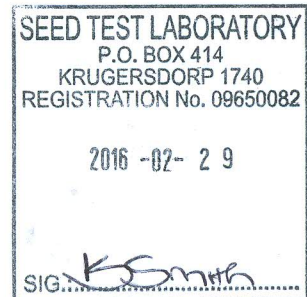
Code Number: 675E
Reference Number: 160216

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-X-	-X-	-X-	-X-	10	-76-	-7-	-0-	-9-	-8-

Inert matter:

Germination method: TP:20<=>30°C

Remarks: COATED



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Forage Sorghum SSG1000
 Botanical Name: Sorghum spp.
 Date sample received: 2016-02-18
 Weight of submitted sample (gram) 1333 gram

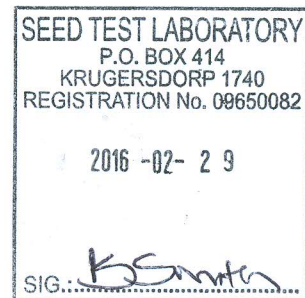
Code Number: 787/35
 Reference Number: A164/16

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-100-	-TR-	-0.0-	-TR-	10	-82-	-0-	-0-	-10-	-8-

Inert matter: Broken seed

Germination method: BP:20<=>30°C

Remarks:



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the **National Department of Agriculture's ISTA Accredited Seed Testing Station** in terms of the Plant Improvement Act, 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Eragrostis Ermelo
Botanical Name: Eragrostis curvula
Date sample received: 2016-02-08
Weight of submitted sample(gram): 775.7 gram

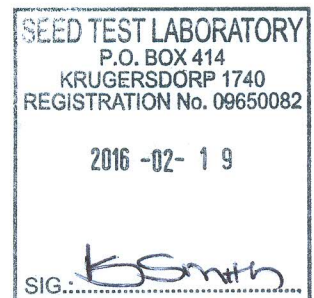
Code Number: 769/1E
Reference Number: 010216

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
X	X	X	X	10	-72-	-0-	-0-	-3-	-25-

Inert matter:
Weed:

Germination method: TP:20<=>30°C

Remarks:



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.



SEED TEST LABORATORY - Advance Seed
 PO Box 414, Krugersdorp 1740
 Tel: 011-762 5261
 Fax: 011-762 4111

as registered with the National Department of
 Agriculture's ISTA Accredited Seed Testing
 Station in terms of the Plant Improvement Act,
 1976 (Act 53 of 1976)

Reg. No. 94/01260/07
 DIV. Seed Control Reg. No. 68050001

ANALYSIS OF SEED SAMPLE

INFORMATION AS STATED BY SENDER:

Kind and Variety: Eragrostis Ermelo
Botanical Name: Eragrostis curvula
Date sample received: 2015-08-26
Weight of submitted sample(gram): 741.5 gram

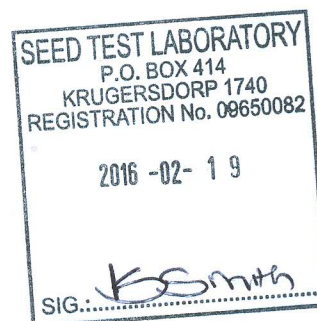
Code Number: 769/1
Reference Number: A514/15

PHYSICAL PURITY (% Calculated by Mass)				GERMINATION (% Calculated by Number)					
Pure seed	Inert matter	Other seeds	Other material (Total of 2 and 3)	Duration of test (days)	Normal seedlings	Hard seeds	Fresh seeds	Abnormal seedlings	Dead seeds
1	2	3	4	5	6	7	8	9	10
-99.5-	-0.4-	-0.1-	-0.5-	10	-78-	-0-	-0-	-2-	-20-

Inert matter: Broken caryopsis, sand, chaff
Weed: 0.1% (4) Eragrostis plana

Germination method: TP:20<=>30°C

Remarks:



Important: These results are applicable to the submitted sample and not necessarily to the seed lot from which the sample was taken. The percentage seed indicated in column 1 may include seeds from other species not visually distinguishable from the seed kind indicated against the botanical name.