Soil quality as a key success factors in sustainable rehabilitation of kimberlite mine waste

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Synopsis

‘Soil quality is the capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health’.

In the long-term, vegetative rehabilitation of mining wastes aims at, as far as possible, the proper ecological integration of the reclaimed area into the surrounding landscape, which is sustainable and requires minimal maintenance. A certain succession pattern is therefore needed. Recent ecological concepts recognize the role of the substrate’s quality and nutrients in affecting the rates and directions of succession patterns. Although pedogenesis and eventually soil quality in mine waste are not well known, monitoring of soil quality parameters in kimberlite mine tailings reveal a remarkable establishment and or improvement of specific soil quality indicators. During the same time the vegetative cover’s total functionality as well as reproductive ability improved.

Functions of soil, and thus soil quality, can be assessed at the field, farm, ecosystem, pedosphere, and global scale. It is recognized, however, that management of soil becomes increasingly difficult at larger scales, but for demarcated mine waste sites it is possible to ameliorate and manage and assess soil functions and quality. Therefore the significance of the study is the following: soil functions and quality become inseparable from the idea of system sustainability, and are considered as key indicators of ecosystem sustainability on rehabilitated mine tailings material.

Introduction

Early scientific endeavours recognized the importance of categorizing soil type and soil variables or properties land or soil use, especially for agricultural purposes. In more recent years, due to concerns with soil degradation and the need for sustainable soil management in agro systems, there has been a renewed scientific attention to soil variables. Coupled with this is the idea of soil use, which has emphasized the value of soil and soil properties for a specific function. Generally, modern concerns with soil quality evolve around the various functions that soils perform in ecosystems. This ecological approach to soil recognizes soil-human interactions, and the relationship of land managers to soil (Richter, 1987). Thus soil quality becomes inseparable from the idea of system sustainability, and is considered a key indicator of ecosystem sustainability. The emphasis on soil quality shifts away from suitability for use to whether soil functions are operating at some optimum capacity or level within an ecosystem. However, optimum capacity in the case of anthropogenic soils, is undefined. The challenge lies with the creation of some capacity in the rehabilitation phase, which will improve on that over time. Only after many decades (or millenniums) can one look at the optimization of certain soil characteristics that influence soil quality.

Placing a value on soil’s specific function, purpose or use leads to the concept of soil quality. However, in contrast to water and air, for which the function can be directly related to human and animal consumption, the function placed on soil is often diverse and usually not directly linked or involved in human health. Thus, the concept of quality is relative to a specific soil function or use. Although soil may have a wide array of possible functions, the following functions of special importance and significance have been identified:

Doran and Parkin, (1994)

- As a medium for plant and biological production
- As a buffer or filter to attenuate or mitigate various environmental contaminates and pathogens, and
- As a promoter of plant, animal, and indirectly human health. Soil Science Society of America (1995).
- Sustaining biological activity, diversity, and productivity

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- Regulating and partitioning water and solute flow
- Filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials
- Storing and cycling nutrients and other elements within the earth's biosphere.

Warkentin (1995)

- Recycling organic materials to release nutrients and energy
- Partitioning rainfall at soil surface
- Maintaining stabile structure to resist water and wind erosion
- Buffering against rapid changes in temperature, moisture, and chemical elements
- Storing and gradually releasing nutrients and water
- Partitioning energy at the soil surface.

Anthropogenic soils derived from mine waste do not have all these functions on the same level as normal soils; in fact, some of them do not even exist prior to amelioration and rehabilitation. The primary purpose of rehabilitation of these soils is to create or improve on these functions to such an extent that the soil will eventually react like a normal soil.

Soil quality can be assessed only by measuring properties and therefore involves both an observer and an interpreter. The range of observers, from individuals to interest groups to society as a whole, and the concomitant range in their value systems, ensure diverse views on soil function and consequently on measures of soil quality. In new horizons and soil units, as in the anthropogenic soils, it is much more the case. Functions of soil, and thus soil quality, can be assessed at the field, farm, ecosystem, pedosphere, and global scale. It is recognized, however, that management of soil becomes increasingly difficult at larger scales. Management of new ecosystems and new soils are even more difficult due to the lack knowledge, experience, literature, or any references. Soil, and consequently soil quality, cannot be managed at the global scale. Many aspects of soil quality can be addressed, however, in a practical way at the lower scale.

Defining soil quality

Early concepts of soil quality dealt mainly with various soil properties that contribute to soil productivity, with little consideration of a definition for soil quality itself. However, mere analysis of soil properties alone, no matter how comprehensive or sophisticated, cannot provide a measure of soil quality unless the properties evaluated are calibrated or related against the designated role or function of the soil. Thus, implicit in any definition of soil quality is an understanding of the stated function of the soil, or what the soil does. The following definitions were given for soil quality:

Anderson and Gregorich (1984)—'the sustained capacity of a soil to accept, store and recycle water, nutrients and energy'.

Gregorich and Acton (1995)—'the soils capacity or fitness to support crop growth without resulting in soil degradation or otherwise harming the environment'.

Larson and Pierce (1991)—the capacity of a soil to function within its ecosystem boundaries and interact positively with the environment external to that ecosystem'.

Soil Science Society of America (1995)—'soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation'.

Doran *et al*. (1996)—'the capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health'.

These definitions imply that soil quality has two parts: an intrinsic part covering a soil's inherent capacity for crop growth, and a dynamic part influenced by the soil user or manager. The latter underlines the lessons of history that poor management can degrade good quality soils. Generally, dynamic soil quality changes in response to soil use and management (Larson and Pierce, 1994).

Inherent soil quality

The quality of any soil depends in part on the soil's natural or inherent composition, which is a function of geological materials and soil forming factors (parent material, topography, climate, biota, and time). Attributes of inherent soil quality, such as mineralogy and particle size distribution, are mainly viewed as almost static and usually show little change over time. It is generally recognized that some soils have poor natural quality and are not fit or suitable for a specific purpose. In some cases, due to adverse management and/or climatic effects, a soil that originaly possessed good inherent quality can deteriorate (e.g. erosion, salinization, acidification, compaction, loss of organic matter, etc.). New soils, e.g. anthropogenic mine tailings, could have poor qualities (as described above), but not due to deterioration, but to infant stages of soil developing, i.e. pedogenesis. Characterization of inherent soil quality for crop production or vegetation support, i.e. rehabilitation, also involves consideration of extrinsic factors, those factors apart from soil that influence crop yield (Janzen *et al.*, 1992). These factors include such things as climatic (rainfall, evaporation demand, and air temperature), topographic, and hydrologic parameters. Generally, inherent soil quality for crop production cannot be evaluated independently of extrinsic factors.

Dynamic soil quality

Dynamic soil quality encompasses those soil properties that can change in response to human use and management. In general, a management system would be viewed as sustainable only if it maintains or improves soil quality (Larson and Pierce, 1994). As implied in the terminology, attributes of dynamic soil quality are subject to change over relatively short time periods. For example, total organic matter may change over a period of years to decades, whereas pH and labile organic matter fractions may change over a period of months to years. In comparison, microbial biomass and populations, soil respiration, nutrient mineralization rates, and macro porosity can change over a period of hours to days. Thus, maintenance and/or improvement of dynamic soil quality deals primarily with those attributes or indicators that are most subject to change (e.g., loss or depletion) and are strongly influenced by management practices. Management of new soils is even more difficult, because of the dynamic nature of its characteristics and due to a lack of literature references and experience etc.

Mine tailings are a typical example of new soils (anthropogenic soils) and in most cases these materials are not in equilibrium with natural physical and chemical reactions, e.g. water store and release balances, weathering of primary minerals, leaching of ions and redox potential.

Soil quality and land sustainability

Soil quality is considered to be a key element of sustainable vegetation establishment, e.g. agriculture or rehabilitation (Warkentin, 1995). Overall, sustainability refers to the productivity, economic, social, and environmental aspects of land use systems (Smyth and Dumanski, 1995). Generally, the main areas involved in rehabilitation and agricultural sustainability are as follows: maintaining or improving farm productivity; avoiding or minimizing adverse impacts on natural resources and associated ecosystems; maximizing the net social benefit derived from the system and promoting flexibility of systems to manage the risk of climate and other factors. Thus, although sustainability issues are much broader than soil quality, the strong emphasis on maintaining the natural resource base ensures that maintaining good soil quality is an integral part of sustainable vegetation establishment (Miller and Wali, 1995).

As indicated earlier, the concept of 'quality' implies purpose, use and value. Generally the means to assess rehabilitation sustainability is by identifying indicators that reflect an attribute or sets of attributes of sustainability. Such indicators are considered tools to both warn of deleterious environmental changes and to compare rehabilitation practices. The biggest challenge in the rehabilitation of mine waste is to create a sustainable ecosystem, which can look after itself, even in a low soil use concept (high production is not required from these new soils).

Evaluating soil quality

A useful framework to evaluate soil quality is based on the following sequence: function, processes, attributes or properties, attribute indicators, and methodology. Soil quality is evaluated on the basis of the function in question. Functions deal with 'what the soil does', or 'what the soil is asked to do'. Each function can be characterized by specific soil processes that support the function being imposed upon the soil. Soil quality attributes can be defined as measurable soil properties that influence the capacity of the soil to perform a specific function (Acton and Padbury, 1993). Generally, attributes describe a critical soil property involved with the process or processes underlying a function. The attribute, or soil property, is most useful when it reflects or measures change in the process. In many cases the specific property may be difficult to measure directly, so an indicator (an a associative property, i.e., surrogate or proxy) or pedotransfer function (a related property; Bouma, 1989) can be used to serve as an indirect, practical measure of the attribute. Indicators can represent a single attribute or a set of attributes. (see Table I)

Soil function on a kimberlite tailings dam

In plant production, the function of soil is to nurture and sustain plant growth. In the case of mine tailings it is the successful establishment of a vegetative cover. This function is related to the efficiency with which soil provides essential nutrients, substrates, and environment to support the conversion of CO_2 to organic molecules using energy from sunlight (via photosynthesis). The function of soil for vegetation production can be subdivided into several components as follows: provide a medium of plant growth; regulate and partition water; gas and energy flow; and serve as a buffer or filter system. Evaluating these function components, to assess a soil for its quality to sustain plant growth, involves considering the soil's chemical, physical, and biological properties. Table II lists the functions of a soil related to plant growth and some of their characteristics. These are applicable for normal and anthropogenic soils.

Typical examples of soil function on a tailings dams are:

- Regulate temperatures for ideal germination conditions
- Store and release water in the upper profile to sustain germination even under vulnerable conditions such as drought and severe windy conditions.
- Regulate gas for sufficient air movement during the entire life cycle of a plant
- Promote root growth, especially in the infant stage
- Supply and cycle plant nutrients
- Buffer the dynamic soil characteristics to screen toxic elements, e.g. salination, sudden change in pH and redox potential.

Table I

Example of a framework for evaluating soil quality of soils (capacity to perform a specific function, e.g., medium for plant growth)

Process	Attribute or property	Indicator for attribute	Possible method for measuring attribute
Capacity to accept, hold and release water	Infiltration, water-holding capacity, permeability	Infiltration rate, Water retention curve Hydraulic conductivity	Infitrometer Tension plate Permeameter
Capacity to accept, hold, and release energy	Organic matter Labile organic matter	Organic carbon Microbial biomass Carbohydrates Macro organic matter	Combustion Chloroform fumigation Acid hydrolysis Dispersion/sieving
	Particle size	Clay	Hydrometer

Table II

Characterizing the main function components of a soil for crop production

Function component	Function characteristics/processes
Medium of plant growth	Suitable medium for seed germination and root growth Absence of adverse chemical conditions (acidity, salinity, sodicity) Supply balance of nutrients Suitable medium for microbes (nutrient cycling, decomposition) Promote root growth and development
Regulates water	Receive, store, and release moisture for plant use Adequate water retention to buffer and reduce effects of drought Adequate infiltration and storage capacity to reduce runoff
Regulates gases	Accept, hold, and release gases Adequate air movement and exchange with atmosphere
Regulate energy	Store, release (recycle) energy rich organic matter
Buffer or filter	Accept, hold, and release nutrients Sequester energy compounds and/or biotoxic elements Detoxify substances harmful to plants

Results of amelioration after three years

The results obtained from a rehabilitation experiment on kimberlite tailings from Cullinan diamond mine is taken as an example of improvement of soil quality and function.

Background

The kimberlite tailings were deposited approximately in 1998 by means of a spigot system at a overall slope angle of 12° at a short terrace method. Erosion and poor vegetation establishment characterized the site prior to 2002. The specific slope is facing east with a slope angle of ± 12°. The site is situated in between two hills, and the northern hill could have an effect on the moisture regime on the northern most trial plots due to a shading effect in winter time.

In 2002 the mine decided to do some experimental work to identify alternative methods to establish proper vegetation cover to reduce the erosion. The experimental project was divided into different phases e.g.:

- Site characterization
- Material characterization and identification of potential negative growth medium qualities
- Preliminary design of experimental work with identification of broad objectives
- Validation with recommendations
- Final design with detail objectives and projected/anticipated output results
- Operational layout
- Establishment of trials (October/November 2002)
- Monitoring and assessments (April 2004 and April 2005)

Experimental layout and methodology

Appendix A shows the site layout of the experimental projects. The specific experimental blocks that are relevant to this paper are Blocks A and Block B. Additional experimental work was conducted in the same sequence and also in 2003 but they are not relevant to the discussion of this paper. The methodology, results and discussion of results will focus only on these two areas. Each block consists of a 20 m x 20 m area. The area was unfortunately too small to have 3 replications for each trial to comply with statistical analytical requirements, but composite sampling was done during all the monitoring programmes. The final samples for analytical purposes were taken from a mixture of ten samples from each site.

The material was characterized and all soil quality indicators and potential negative properties were identified. The major amelioration techniques that were applied could be summarized as follows:

- Physical amelioration with garden forks to a depth of 300 mm to break up any crust or compaction
- Organic carbon in the form of sewerage sludge was added to the tailings material at rate of 50 m^3 per ha on Block A and 20 m^3 per ha.
- An appropriate fertilizer [4:3:4 (36)] was applied at a rate of 1 000 kg /ha and was worked into the growth medium to a depth of 200 mm. Another fertilizer application was done in January 2003 by means of 300 kg/ha of LAN. This was followed up by 300 kg/ha LAN in October 2003, January 2004 and October 2004.
- A suit of grass species, which are adapted to the climatic area, growth medium properties, and water quality, were established on the slope by means of seeding and hand plants in December 2002 and January 2003.
- The seed was covered with phragmites mulch to obtain a ±60% shade effect
- Irrigation was applied after seeding for a period of one year.

The classification of the irrigation water according to the SA Water Quality guidelines (DWAF) is as follows:

- Salinity – Class 2
- Sodicity – Class 2
- Toxicity – Class 1 (Cl, Na, B).

The water quality of the irrigation water was fairly good and suitable for irrigation purposes.

The main objective of the trial was to find the most cost-effective and sustainable method to improve the total water regime (increasing infiltration and lowering evaporation) and pedo-chemical conditions of the growth medium to sustain normal plant growth. However, the results of the monitoring programmes reveal that certain pedogenic processes have taken place in the ameliorated tailings over a period of three years.

These pedogenic processes and associated soil quality indicators are discussed in this paper and not so much the total results with respect to the vegetation quality performance or other ecological assessments.

During the active part of the growth season (October to March), there is no shading effect on the trial plots, which could have any major influence on the performance of the vegetation on the northern most plots in relation to the water regime.

Results

The results are displayed in Table III and Appendix B and Figures 1 to 7.

One of the main soil characteristics, which have had an influence on many other quality indicators and soil functions, is particle size distribution, as shown in Table III.

Amelioration of the tailings prior to seeding focused on the improvement of specific soil qualities, as mentioned above. The large sandy component of the Cullinan tailings cause a negative water retention regime and that together with the colour makes it difficult for seed to germinate due to hot and dry conditions. Seed contact with the soil/tailings matrix was also poor due to the large sand fraction. The high salinity and pH conditions also contribute to poor growth conditions.

The results shown in Figures 1–7 are examples of how the soil properties and qualities change over a period of 3 years. Tailings A represents the areas where compost was added at a rate of 50 m^3 per hectare and B represents the areas with 20 m^3 per ha.

Discussion of results

Organic carbon is one of the major soil constituents that influence many other soil properties and qualities, e.g. cation exchange capacity, water retention, regulates gas and water, buffer chemical reactions, etc. Normal oxidation of carbon material takes place and reduces the total carbon content until it reaches a constant in every specific soil or medium. Clay content, atmospheric temperature, water regime, etc. play a role in the oxidation process. In the case of the kimberlite tailings from Block A, the organic carbon content was 0.2% after amelioration and it decreases to 0.15 %. It is postulated that the decrease was due to normal oxidation processes. In the case of Block B, which received much less compost, it increases from 0.025% to 0.08 (Figure 1). The increase could be due to root die-back and decomposition of the mulch. It is anticipated that the equilibrium value for organic carbon in kimberlite tailings in the Cullinan area is between 0.025 and 0.08 %.

Table III

Mechanical analyses 0–30 cm (composite sample, prior to seeding and amelioration) % mass

C sand	22
M sand	37
F sand	24
VF sand	6
C silt	1
F silt	6
Clay	4
Texture	Sand

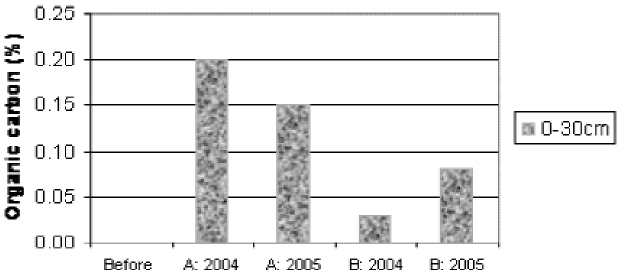

Figure 1—Organic carbon content in upper 30 cm of two tailings treatments

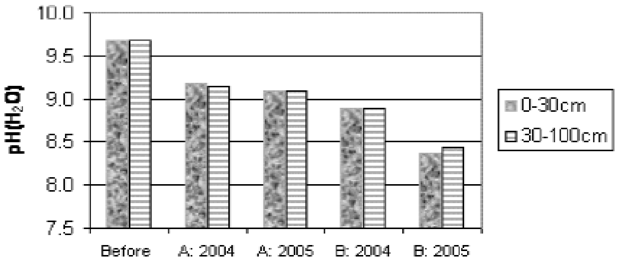

Figure 2—Change of pH over time, depth and treatment

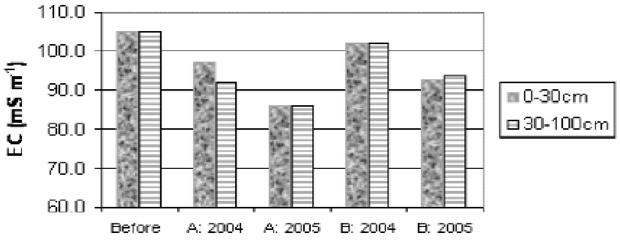

Figure 3—Decrease of salinity with time and treatment

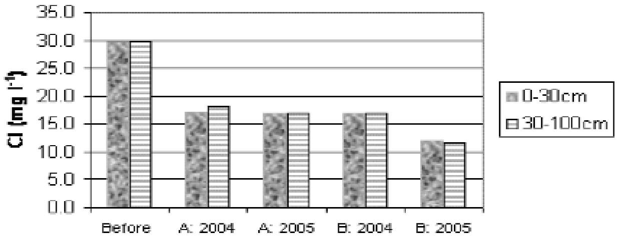

Figure 4—Decrease of Cl with time and treatment

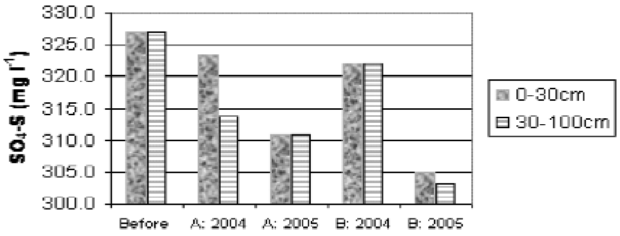

Figure 5—Decrease of SO_4 with time, treatment and depth

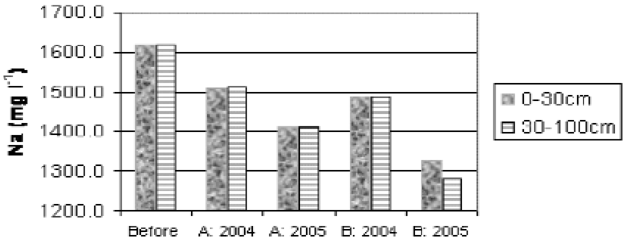

Figure 6—Decrease of sodium with time, depth and treatment

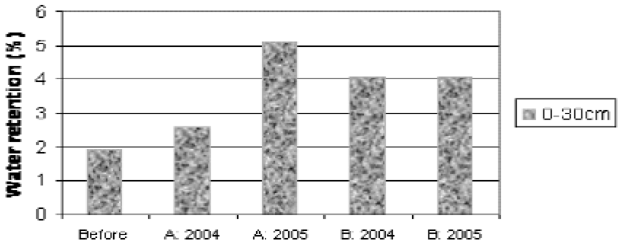

Figure 7—Improvement of water retention with time

Figure 2 indicates a change in pH from 9.7 to approximately 8.7 over a period of 3 years for both mediums. A pH closer to 6.8 would reflect a better soil quality, but it would be very difficult to achieve this for a kimberlite tailings due to abundant cations present in the material and also due to the relative quick weathering of the primary minerals in the kimberlite .

Figure 3 reveals the decrease in salinity with time and treatment in both mediums, but virtually no change in depth. Although 100 $mS.m^{-1}$ is not extreme for plant growth, the ideal is below 50. Figures 4 and 5 are just a support for Figure 3.

Sodium is not a phytotoxic element, but the side effects could have various other negative effects, e.g. potassium deficiency, soil dispersiveness, or decrease in hydraulic infiltration. Therefore it would be to the benefit of many soil qualities to reduce the sodium content. In both mediums the sodium decreases with time, as shown in Figure 6.

The application of compost is intended to improve on water retention, and Figure 7 shows this to occur. It is speculated that the water retention was also improved by soil structure formation, root development and the weathering of primary minerals into secondary minerals.

Conclusions

Although soil quality can be simply defined as a soil's 'fitness for use', it is in reality a complex concept and significantly more challenging in its assessment than air or water quality. Ongoing weathering of primary minerals (which are predominant), increase in exchange capacity, leaching, change in texture and structure are just some of the soil attributes that influence total soil quality and land use capability.

Basic soil properties and qualities improved over a short period of time in kimberlite tailings after amelioration and vegetation establishment. It is anticipated that these improvements will be more pronounced over a longer period of time and it will contribute to pedogenic processes to ensure a real soil in the near future.

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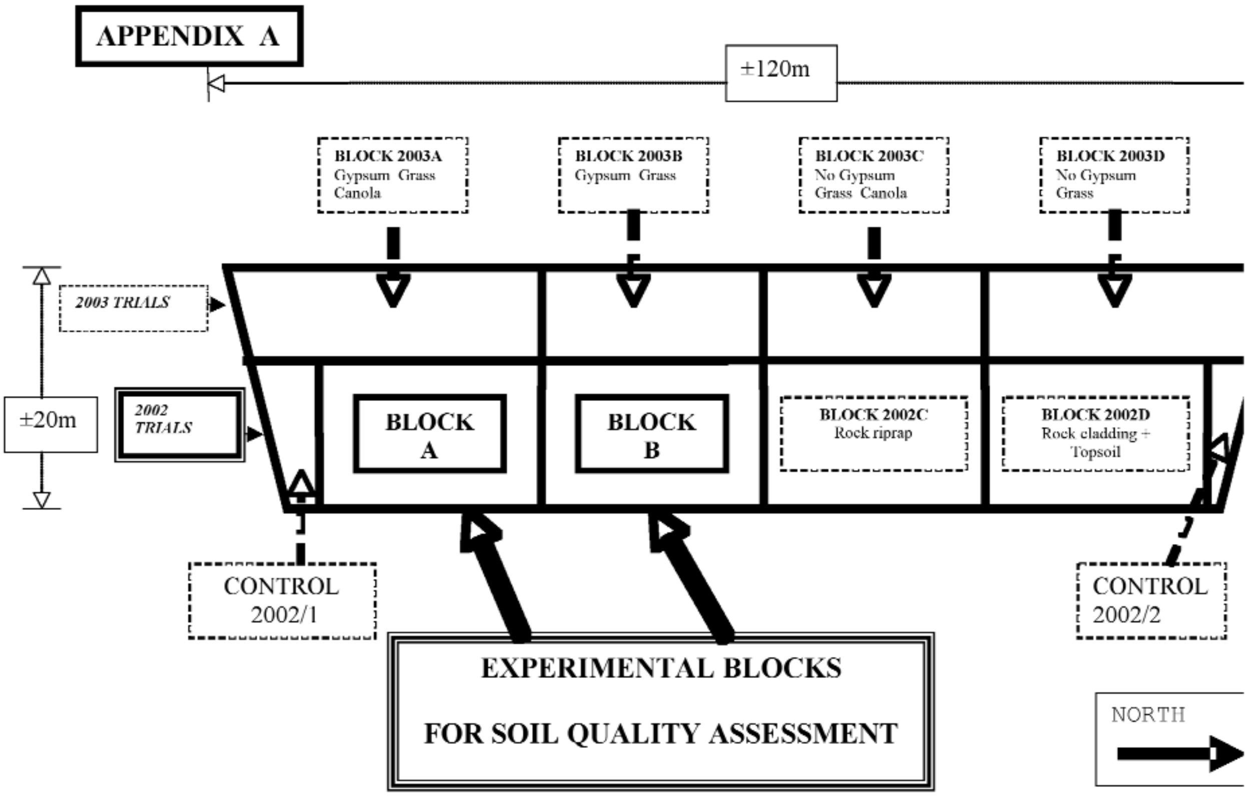
Appendix A



Township Wall: Diagram showing lay out of research trial blocks for 2002 and 2003 Trials

Appendix B

Summary of chemical analysis of tailings for the 0–30cm depth zone

Analyses	Average for all Before (2002)	Compost	Block A			Block B		
			2003	2004	2005	2003	2004	2005
1. pH (water)	9.7	7.48	10.0	9.2	9.1	10.1	8.9	8.4
2. pH (KCl)	7.7	-	-	7.6	7.4	-	7.9	7.9
3. EC (mS/m)	105	293	106	97	85	106	101	92
4. Cl (mg/liter)	30	-	-	17	16	-	17	12
5. SO_4(mg/liter)	327	-	-	322	311	-	322	305
6. NO_3(mg/liter)	1610	-	-	1510	1405	-	1490	1320
7. HCO_3 (mg/liter)	602	-	-		523	-		544
8. P (mg/kg)	2.7	40.76	-	5.6	3	-	5.4	6
9. Exchangeable cations :		-	-			-		
(cmol/kg) Na	5.67			4.6	6.9		5.46	6.0
K	1.79			1.56	2.9		2.17	2.7
Ca	11.01			7.04	10.8		8.26	10.2
Mg	1.79			1.83	3.5		2.56	3.6
10. CEC (cmol/kg)	16.04	-	-	10.97	11.51	-	13.23	13.34
11. Organic carbon %	0.0	15.92	-	0.20	0.15	-	0.025	0.08
11. ESP(Na /CEC)	34.6	-	-	41.9	60.04	-	41.3	45.0