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IRRIGATION OF REHABILITATED MINE LAND WITH CIRCUM-NEUTRAL MINE WATER

by

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DECLARATION

I hereby certify that this dissertation is my own work, except where duly acknowledged.
I also certify that no plagiarism was committed in writing the dissertation.

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Abstract

Utilizing mine water for irrigation on rehabilitated land will be beneficial for both the mining and agricultural sectors. Mpumalanga has thousands of hectares of rehabilitated land that were considered high-potential agricultural land before mining commenced. Years of research have been done on the use of mine water as an alternative water source for irrigation. The key objective of this study was to determine if circum-neutral mine water can be used for irrigation on rehabilitated land and what factors influence the irrigability of rehabilitated land.

A soil survey, using a dryland classification system commonly used in South Africa, was done over an area of rehabilitated land at Mafube Colliery, Mpumalanga. A pivot irrigation system was established on this rehabilitated area to identify and determine the relationships between soil factors and plant growth. High variability in the soil's physical and chemical properties were identified. The high variability identified in the rehabilitated land combined with the dryland soil potential system was used to identify different sampling areas to determine the factors that influence the irrigability of rehabilitated land. While it was not possible to grow a commercial crop in the first season, weeds were used as a surrogate for crop production to determine which factors affected growth. The results obtained from the weed assessment showed that there was a relationship between both chemical and physical properties of the soil and weed growth. Physical soil conditions, such as restrictive layers and severe compaction had a more significant effect than chemical properties.

In the second cropping season, it was possible to establish a pasture mixture under irrigation on the rehabilitated land. Different hypotheses around the irrigability of the rehabilitated land were developed and tested. The final topography of the rehabilitated land proved to be a major factor influencing irrigability. Severe water ponding created difficult growing conditions in the rehabilitated field where poor growth was recorded. It was concluded that when factors like topography and infiltrability are combined with a dryland classification system the accuracy in predicting suitability for irrigation increases. If the correct rehabilitation methodology is followed using the guidelines (Land Rehabilitation Guidelines for Surface Coal Mines), there is no doubt that a more uniform site with acceptable conditions for irrigation and dryland could be created. This study proved that irrigating rehabilitated land with mine water is definitely worth pursuing and will be beneficial for mining and agriculture.

Chapter 1: Introduction

Mining takes place over a finite period, but the legacy of mining is more permanent; this implies that what is left post-mining is arguably a lot more important than what is mined out of the earth. This is why the rehabilitation of mined areas that meet the standards of the Land Rehabilitation Guidelines for Surface Coal Mines (LaRSSA, 2019), is required. When a mined area is not rehabilitated properly or to a specified standard, it can lead to severe impacts on the environment and local communities, through pollution of the soil and water, through soil degradation and through a permanent decrease in land productivity.

The mining industry in South Africa produces large volumes of mine-affected waters, that are difficult to manage, and expensive to treat. Since South Africa is a water scarce country, a noteworthy opportunity arises to irrigate crops on rehabilitated land with suitable mine-influenced waters, providing that any environmental impacts are acceptable. The availability of large volumes of mine-affected water and large tracts of unfarmed land or rehabilitated land owned by mines creates an opportunity to utilise this poorer-quality mine water for irrigation.

Infiltration and drainage rates of the soil are very important aspects for irrigated and arable conditions. Infiltration is the downward entry of water into the soil, it can also be defined as the flow from water aboveground into the subsurface (Ferré & Warrick, 2005). Rehabilitated soils are prone to compaction which usually results in low infiltration and drainage rates (LaRSSA, 2019).

Currently, there are guidelines for irrigation with mine affected waters on unmined soil, but there are no guidelines specifically for the irrigation of rehabilitated land, or guidelines for rehabilitation of mined land to irrigable standards. This research has been designed to assist in the development of such guidelines.

The main objective of this study was to measure the variation in soil properties on the rehabilitated field and to correlate that to irrigation crop fields, to determine which properties are the most important. Secondly, to asses a dryland land capability classification tool to determine its use as an irrigation land capability tool. Another aim was also to successfully irrigate a crop with mine water on rehabilitated land.
Hypotheses:

- Rehabilitated land could be valuable for gainful use of mine water for irrigation.
- High variability is expected in the soil’s physical and chemical properties

- Growth will be spatially highly variable over the rehabilitated area, because of the extreme differences in soil type and characteristics.
- Rehabilitated land will be more variable and less suitable than unmined irrigable land for irrigation, due to a number of factors related to the nature of rehabilitated land.
- Irrigation with circum-neutral, gypsiferous mine impacted water will not have a negative effect on crop growth.
- A dryland classification system may be flawed if used to assess productivity of irrigated rehabilitated areas.
- Negative impact from the contaminating salts in the mine water, will precipitate and be contained in the rehabilitated profile pit, thus, not reaching and affecting ground water sources.
- Yields will be depressed where poor quality soils were imported resulting in nutrient deficiencies.

This study focused on key challenges facing irrigation with mine water on rehabilitated land, and how to overcome them or possibly prevent them from materialising. Concluding the findings of this study and research, key focus points and challenges regarding rehabilitation and irrigation with mine water are addressed. This study also outlines future work that is needed to generate guidelines for irrigation of rehabilitated land.

Chapter 2: Literature Review

2.1 Introduction

Mining is the fifth largest industry in the world. South Africa is ranked as the 6th largest coal-exporting nation and is home to 3.5% of the world's coal resources (Chamber of Mines, 2017). A rapid increase in South Africa's mining activity, especially in Mpumalanga, has led to concerns that large tracts of high-potential arable land are being lost (BFAP, 2015). Mpumalanga contains almost half of South Africa's high potential arable land (Simpson et al., 2019). While coal mining generates a great income, it is not sustainable, and is only a temporary economic activity. This implies that what is left post-mining, is arguably a lot more important than what is mined out of the earth.

When a mined area is not rehabilitated properly or to a specific standard, it can lead to severe impacts on local communities and the environment, through soil degradation, and soil and water pollution. The process of land degradation is different and unique for every site or area (Barkemeyer et al., 2015). This is why rehabilitation of mined areas that meets the standards of the Land Rehabilitation Guidelines for South Africa (LaRSSA, 2019) is one of the most important processes required to gain full mine closure. Since the Minerals Act of 1992, closure planning has been a requirement in South Africa, which means that financial provisions must be made, rehabilitation must be undertaken and a closure certificate must be applied for (Watson & Olade, 2019).

South Africa has low and variable rainfall, with 66% of the country classified as semi-arid to arid (Jovanovic et al., 1998). Water availability for irrigation is limited in South Africa and in addition to scarcity, water contamination and mine water decanting can create a severe problem if not properly managed (Annandale et al., 2006). With the increasing population, Annandale et al., 2001 stated that it is crucial that agricultural land and resources be maintained and utilized effectively. Intensive research on mine water irrigation, especially in Mpumalanga, was done over the past 30 years (Annandale et al., 1999; 2002; 2006; 2009; Du Plessis, 1983; Jovanovic et al., 1998; 2002). This research laid the foundation of this study and guided the approach to the consideration of rehabilitated land for irrigation.

Open-cast mining severely alters the landscape and much physical disturbance of the soil is involved (Paterson et al., 2018). Limpitlaw et al., 1997 highlights how mining completely destroys the land surface and how such areas need to be rehabilitated. Physical and chemical properties change during mining and rehabilitation, and mitigation of these changes are much more complicated than most mines expect and proper rehabilitation is easily underestimated.

The objectives of this study are to determine: (1) the effect of mine water as an irrigation source on rehabilitated land; (2) the variability of soil properties of rehabilitated land; (3) the effect of the soil variability on crop growth; (4) the irrigable potential of rehabilitated land; and (5), how to develop rehabilitation standards to an irrigable potential and (6) how to use these findings to possibly update the current rehabilitation guidelines. The impact of gypsiferous mine water irrigation on rehabilitated land is researched and monitored over a two year period to determine the sustainability and environmental impact.

2.2 Terminology

Much of the terminology around mining-related rehabilitation is used incorrectly and loosely. It is important to understand each term and what is implied when used and in what context it is used (LaRSSA, 2019). This section provides some clarity and background regarding mine-related terminology.

Land capability is determined by the physical, chemical and biological properties of the soil, it is also the potential of the land to support different land uses (LaRSSA, 2019). The South African Department of Agriculture, Forestry and Fisheries (DAFF) made provisions for land capability classes, presented in Table 2.1. The classification used by the mining industries are indicated in the right column of Table 2.1. Pre-mining land capability is assessed before mining commences and post-mining rehabilitation capabilities should meet the requirements and targets that have been set from the pre-mining capabilities. Agricultural land capability assessments are done prior to mining and provide the basis for determining the rehabilitation standard. Mines are obligated to ensure that there is no net loss in land capability (Limpitlaw et al., 2005).

Table 2.1: DAFF land capability classes compared with the four used by the mining industry (adapted from BFAP, 2015)

Land capability class	Soil depth (mm)	Classification by DAFF	Classification used by mining
I	>800	Arable land suitable for very intensive cultivation	Arable land
II	>700	Arable land suitable for intensive cultivation	
III	600-800	Arable land suitable for moderate cultivation	
IV	500-700	Arable land suitable for light cultivation	
V	400-600	Grazing land suitable for moderate grazing but not forestry	Grazing
VI	300-500	Grazing suitable for moderate grazing	
VII	100-400	Grazing land suitable for light grazing	
VIII	<100	Wildlife	Wilderness Wetland

The most important part of pre-and post-mining land is a detailed evaluation of the land capabilities, as it is the only objective basis for establishing targets for post-mining land capabilities.

Rehabilitation is the transformation of land from its original condition to a new beneficial condition (LaRSSA, 2019). It can also be defined as the return of disturbed land to a stable, productive and sustainable condition. For mining, rehabilitation of disturbed land results in the return of the land to a stable condition that is capable of supporting permanent use as directed by the mine plan. Revegetation, remediation and reclamation are different phases that form part of rehabilitation (Weyer et al., 2017). A successful rehabilitated area, must contribute to environmental improvement and must be consistent with surrounding values (Limpitlaw & Briel, 2014).

The main focus of rehabilitation is protecting the environment, maintaining productivity and creating the best possible post-mining land capabilities. There are various challenges regarding the rehabilitation process. However, as very large areas are disturbed by mining operations and completely alter the landscape, rehabilitation to the desired standard becomes extremely difficult or even impossible to achieve in some areas. The main limitation is mostly financial shortage. The heavy machinery used to dismantle a landscape should be able to recreate the landscape again using appropriate guidelines, but comes with a cost that can easily be underestimated.

2.3 Coal mining and agriculture in South Africa and the Mpumalanga Province

Commercial coal mining started in 1857 in South Africa and the country was in 2016 the 6th largest coal producer in the world (Chamber of Mines, 2016; Hancox, 2016). More than 50% of the saleable coal in SA comes from the Witbank Coalfields and more than 80% from the whole of Mpumalanga. Most of the nation's coal-fired power stations are situated near the coal mines in Mpumalanga (Hancox, 2016). This is indicative of the highly intensive mining industry in the province.

Agriculture and mining are the key driving forces behind the South African economy (BFAP, 2015). Over 60% of the surface of Mpumalanga is either subject to mining rights or prospecting applications. Mpumalanga contains almost half of the country's high-potential arable land. South Africa has only 1 878 750 ha of high-potential arable land, 46% of this, or just over 864 000 ha, is found in Mpumalanga (BFAP, 2012; Simpson et al., 2019). This is indicated in Figure 2.1.

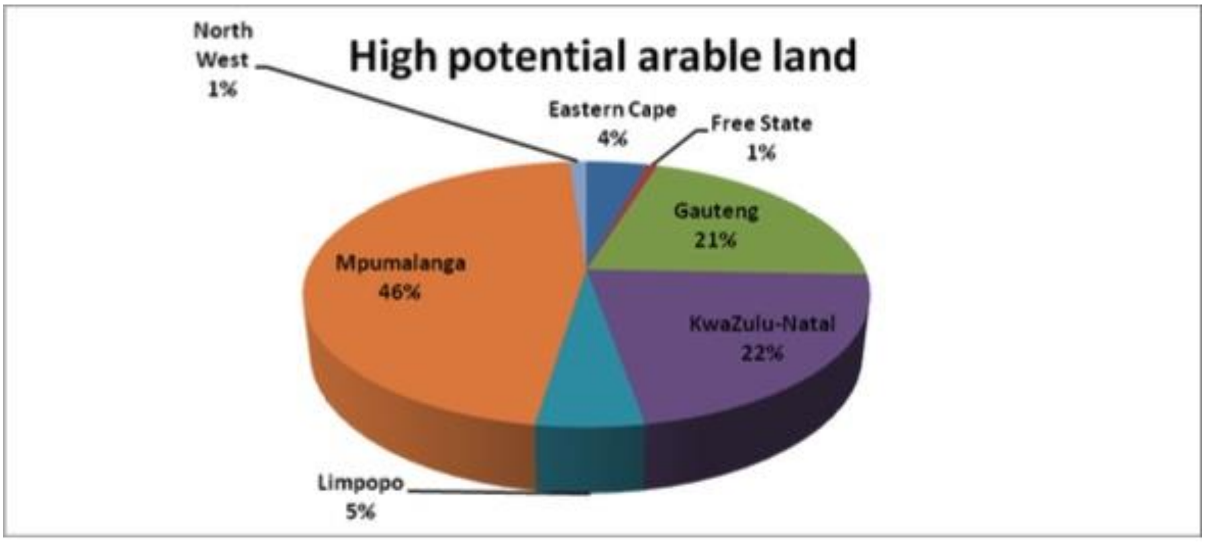


Figure 2.1: High potential arable land in South Africa (BFAP, 2012).

In 2012, 2.6 million hectares of land in Mpumalanga was classified as being under "mining and prospecting". According to BFAP (2015), of the 2.6 million hectares, 670 000 ha were regarded as high potential agricultural land.

Figure 2.2 represents land use applications until 2014 in Mpumalanga. It should be noted that large farm portions are not visible in the figure as it is covered by mining and prospecting areas. The map in Figure 2.2 might seem like an over-exaggeration of the actual reality, but it presents a reasonable indication of the ongoing competition for land between mining and agriculture. However, prospecting land is still used by agriculture until mining begins.

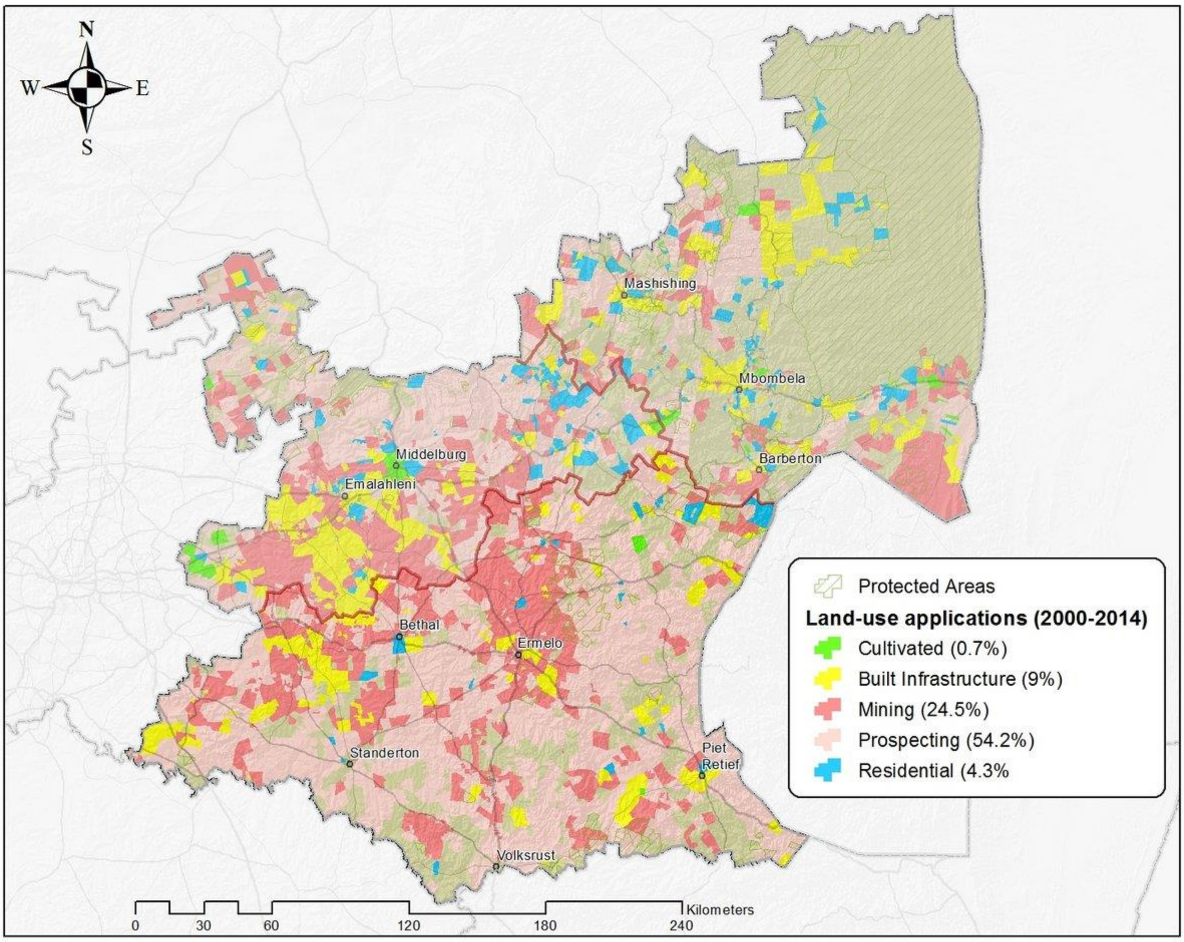


Figure 2.2: Land use applications until 2014 (Zero Hour, 2016).

The significant backlog in the rehabilitation of open-cast mined land, combined with the failure of some rehabilitation efforts, is of great concern and contributes to the problem and tension between mining and agriculture (Simpson et al., 2019). Table 2.2 represents the loss of arable land for the highest two land capability classes, in Mpumalanga. This indicates the impact of current and future mining activities on agriculture and also the importance of rehabilitation according to the guidelines. Class I and II are classified as arable land suitable for intensive cultivation.

Table 2.2: Loss of high-value agricultural land due to mining activities in Mpumalanga (Simpson et al., 2019)

Land Capability Class	I	II	I and II combined
Available	872 007 ha	2 058 727 ha	2 930 734 ha
Existing mining	18 378 ha	34 868 ha	53 246 ha
Mining and prospecting applications	751 326 ha	1 404 224 ha	2 155 550 ha

More than 53 000 hectares of arable land are already lost to mining. It likely to be even greater now, as soil loss may be latent for several years following rehabilitation (Limpitlaw et al., 2005).

3. Mine rehabilitation

Historically, major mining houses put great emphasis on the rehabilitation of mines. Some of the smaller mines were not so diligent with this, but there was still considerable effort to do the right thing. A major reason for this was a lack of financial resources, as coal was originally a controlled product with pricing fixed by the government. Today, society expects mining land to be transferred to new productive uses and closure is required. This includes pre-mining land use or conservation use (Limpitlaw & Briel, 2014). Surface coal mines have a disturbance potential that is unmatched by any other human activity, except for urban development and these disturbed lands require rehabilitation (Weyer et al., 2017). EIAs (Environmental impact assessment), EMPs (Environmental management plan) and land rehabilitation are important features of the legislative framework around mining activities, especially with regard to soil and water resources. These are important processes of particular interest to agriculture, as mine rehabilitation is frequently performed with the intention of returning land to the required level of agricultural use. In practice, however, there is a lack of evidence to suggest that mines are capable of successfully rehabilitating land to pre-mining agricultural potential levels (BFAP, 2015).

When soil is disturbed or moved, the chemical and physical properties change, and, once soil productivity is lost or significantly reduced, it takes many years to regenerate (LaRSSA, 2019). The *Land Rehabilitation Guidelines for Surface Coal Mines* explain in detail the different phases of soil handling during the rehabilitation process. Topsoil is a key resource in rehabilitation and the management throughout the mining lifecycle affects the outcome of rehabilitation. This section briefly touches on the phases of soil handling during rehabilitation and some of the effects on soil associated with rehabilitation.

3.1 Phases of soil handling during rehabilitation

A detailed soil survey carried out by a pedologist is important to define the physical and chemical limitations of the soil. Different soil types and characteristics may require different approaches or techniques with the handling plan (Goosen, 2015). The phases of soil handling discussed in this section are soil stripping, soil stockpiling and soil replacement. The soil survey must be able to define a site-specific materials balance for rehabilitation.

Soil stripping should remove all usable material that can support plant growth. Usable soil is mainly 1 -1 .5 m thick, but occasionally it can be 3 – 5 m thick. This are typically the A and non-plinthic B horizon soils (LaRSSA, 2019). Soil stripping should be done according to the handling plan that was generated through the data collected during the baseline soil survey. According to the guidelines, a good handling plan must indicate the following:

1. Georeferenced survey identifying soil types, horizons and depths to be stripped.
2. Areas to be stripped and the most suitable time for stripping.
3. Where stripped soils are to be placed.
4. The proposed final distribution of replaced soils in terms of both thickness and material used.
5. A detailed soil survey that is able to define a site-specific materials balance for rehabilitation.

It is important to follow the handling plan to prevent unnecessary loss in soil quality that will create conditions not conducive for successful rehabilitation. LaRSSA (2019) emphasises that soils with different characteristics should not be mixed and should be stockpiled separately. One of the main reasons for this is to replace soil materials in the correct location in the rehabilitated catena.

The amount of soil stripped is of cardinal importance and should be closely monitored. When too little is stripped, valuable material for rehabilitation is lost and when too much is stripped, the soil for rehabilitation is contaminated with lower-quality materials that then decreases the overall quality of the replaced soil (Mushia et al., 2016).

Limpitlaw et al., 2005 stated that soil stripping in conditions with a moisture content of 10% and higher leads to compaction in the topsoil stockpile. Ideally, soil stripping and placement should take place during the drier months of the year when rainfall is at its lowest and soils are dry with a low moisture content.

Most South African soils, other than vertisols, are highly susceptible to compaction. Compaction is the single biggest limitation to successful rehabilitation. Prevention of compaction during soil handling should be a priority for all rehabilitation activities. According to LaRSSA, 2019, compaction during stripping is largely dependent on the equipment used. The best practice according to the *Land Rehabilitation Guidelines for Surface Coal Mining* is to use backhoes that strip usable soils that are then loaded onto trucks that only travel on subsoil benches in already stripped areas.

Soil stockpiling is a necessary component of coal mining in South Africa, especially Mpumalanga, where most of the soils have a high arable potential that needs to be preserved (Paterson et al., 2018). Topsoil cannot always be placed directly on mined-out land, therefore, it may be necessary to stockpile the soil for future use. Soil is a valuable resource and growth medium for vegetation, and because stockpiled soil is needed for rehabilitation and mine closure, management of stockpiles at a surface coal mine is of utmost importance. Stockpiling for short periods of time significantly reduces the loss of viable seeds and the production potential remains high (LaRSSA, 2019; Mushia et al., 2016). Again, stockpiling for short periods is not always possible and therefore, it is imperative that every effort be made to minimise the disturbance and associated deterioration of the physical and chemical properties.

Mushia et al., 2016 stated that poor management of stockpiles and topsoil, will lower the rehabilitation potential of the soil and increase the rehabilitation costs. Improving the health and fertility of soils through amendment is crucial for rehabilitation, but can be very expensive. Paterson et al., 2018, concluded that higher stockpiles had higher levels of compaction than shallow stockpiles. The reason for this is that vehicle influence is a lot less with shallower stockpiles and consequently much less compaction of the stockpile.

Good infiltration and drainage are crucial for stockpiles to prevent erosion and soil loss. Compaction reduces the water infiltration rate and therefore aggravates run-off erosion (Weyer et al., 2017). Revegetation of stockpiles is of utmost importance. This ensures a maximum level of biological activity in soil stockpiles to maintain productivity potential (Paterson et al., 2018). Mushia et al., 2016, emphasised that without the addition of lime and fertilizer, stockpiles could not support vegetation growth and maintain productivity. However, this is not a universal rule of thumb, and many topsoil stockpiles can support vegetation. Fertilizer application does increase fertility and assist with growth, but increases the cost of rehabilitation when it is not always necessary.

Soil replacement is when soil is placed over reshaped spoils. In ideal rehabilitation, subsoil is placed on top of reshaped spoil, and then topsoil is replaced on top of the subsoil. Topsoil replacement refers usually to the top 0.5 – 1.2 m of the surface soil. Replaced topsoil is what should provide plants with a rooting medium that stores nutrients and water. In ideal rehabilitated conditions, roots can reach and penetrate subsoil which can also provide a rooting medium and allow water infiltration to deeper depths. Topsoil is a key resource in re-establishing land capability. Soil surveys before mining commence determine the pre-mining land capability and with this, the post-mining land capability is derived.

Compaction is a severe problem which limits the success of rehabilitation in South Africa. Soil compaction generally reduces the amount of water that plants can take up. Obtaining the full required thickness of topsoil with a single lift from a dump truck is important and will minimise unnecessary compaction by limiting the need for heavy vehicles to travel over replaced soil material. While this is the best for minimising compaction in the topsoil, equipment creates compaction layers in the subsoil. Ripping at an adequate depth is required after soil replacement to loosen compacted layers in the subsoil. If subsoil and topsoil are placed together in a single lift, compaction will be minimised, but the top and sub-soils are then mixed, resulting in significantly lower fertility and organic carbon, thereby remedying one problem and creating another. Soils should only be handled during the dry season. This is important for soil stripping and soil replacement. Once soils are compacted, it is difficult to alleviate this problem (Paterson et al., 2018).

LaRSSA 2019, highlight the importance of retaining a soil reserve for any surface subsidence areas that may occur. Depression areas in rehabilitated land are likely to occur and need to be filled to create a free-draining surface and to prevent ponding. If there was no soil reserve kept, it becomes more difficult to refill depression areas and increases the likelihood of use of a different soil type or soil of poorer quality.

Handling soil throughout the mining lifecycle determines the rehabilitation success and the input required to maintain the post-mining land capability potential. The next section will focus on common problems with rehabilitated soil and the effect on land capability.

3.2 Rehabilitated soil limitations and the effect on land capability

In most cases, rehabilitated soils are inferior to natural or unmined soils. This is due to compaction, low fertility, mixing of soil types and surface subsidence. Soil amelioration is necessary for rehabilitation. Unfortunately, amelioration of damage and poor soil condition due to poor rehabilitation is very expensive and most times it is almost impossible to ameliorate to the proper pre-mining capability. The cost of amelioration can exceed the original budget allocated for rehabilitation. This is a difficult situation for mines as the mining operation has ceased for that area but the cost of rehabilitation continues.

Mines have an obligation to ensure that no unnecessary loss in land capability occurs. Land use can be changed and decided by society, but mines must ensure that the decision is made based not on the conditions and circumstances of rehabilitation (Limpitlaw et al., 2005).

Degraded land potential does not only refer to “poor topsoil replacement”, but can also be due to rocky surfaces or dump material covering the area. Rocky surfaces are easy enough to revegetate. However, intensive crop production is less likely where the surface is rocky (Limpitlaw et al., 2005). Soil loss does not always occur after rehabilitation, but sometimes only becomes apparent after 10 or 20 years. Understanding soils is crucial as depth, density and drainage differ for various soil types and profiles which is critical for the successful establishment of vegetation (Limpitlaw et al., 1997).

Compaction of soil caused by machinery is the biggest challenge for rehabilitation. Limpitlaw et al., (2005) state that rehabilitation may be more prone to failure on deep compacted soils rather than shallow compacted soils. Alleviating shallow compacted layers (0-300 mm and 400-600 mm) is much easier than alleviating deep compacted layers (below 600 mm). Conventional tillage methods like ripping, easily loosen the soil down to 600 mm in normal arable soils, but for compacted rehabilitated soil, heavy-duty machinery is needed to achieve the full depth of loosening. Compacted layers or consolidated material below this depth, are not easily alleviated and results in water-logging of roots (Limpitlaw et al., 1997 & Mentis, 1999). Deep compacted layers not only restrict water infiltration and create water-logged soils, but roots are unable to penetrate deeply into the soil to reach nutrients and water stored at deeper levels.

Duplex soils created during rehabilitation are a common occurrence that can drastically reduce arable potential. Tennant et al., (1992), defined duplex soils as texture contrast soils in which the soil horizons differ by at least more than one and a half texture groups. The boundary between horizons in duplex soils is usually sharp and clearly visible. Anthropogenic duplex soils are usually instantly created during the soil replacement process, whereas naturally, duplex soils are formed over long periods of time, usually through erosion. Regardless of the process, duplex soils are almost always associated with either poor infiltrability, run-off resulting in erosion, or water ponding resulting in waterlogged profiles (Thompson, 2008).

3.3 Subsidence impact on surface topography

In time, any action of removing material from the earth and replacing disturbed areas will result in subsidence. The methods used to replace the overburden and to recreate the rehabilitation profile are key determinants in the amount of subsidence that is likely to occur, as is the nature of the overburden. Some subsidence areas may never be noticed with no effect on the surrounding environment while, others are clearly visible with a huge impact on the rehabilitated environment (Canbulat et al., 2020). Circumstances determining subsidence depend on different factors such as the amount of material moved, the depth at which it was removed and the rehabilitation process afterwards. Land subsidence results in substantial environmental problems, such as soil erosion and waterlogged areas which are usually not caused by the rising groundwater level, but rather the depressed surfaces that are closer to the groundwater level (Wang et al., 2017).

Subsidence that forms has a direct effect on the surface topography of the area. The level of the severeness of subsidence impact is related to the post-mining land use of the area. The effect of subsidence on wilderness or grazing land capabilities will be less severe than the effect on arable capability. Topography is one of the most important factors that land capability depends on.

Uncertainty of subsidence occurring and how the final landform will be affected is inevitable. Soft materials compact by much as 15%, while hard materials can expand up to 30% (LaRSSA, 2019). These factors make it difficult to predict the final landform of any rehabilitated area. Subsidence can occur from directly after the rehabilitation process, until 5 – 10 years. More important is the re-establishment of the water table within the rehabilitated profile. As the pit becomes filled, water enables movement of the spoil materials and thus enhances settlement. This makes the prediction even more difficult and shows the importance of monitoring rehabilitated areas for longer periods. Figure 2.3 illustrates the principle of subsidence.

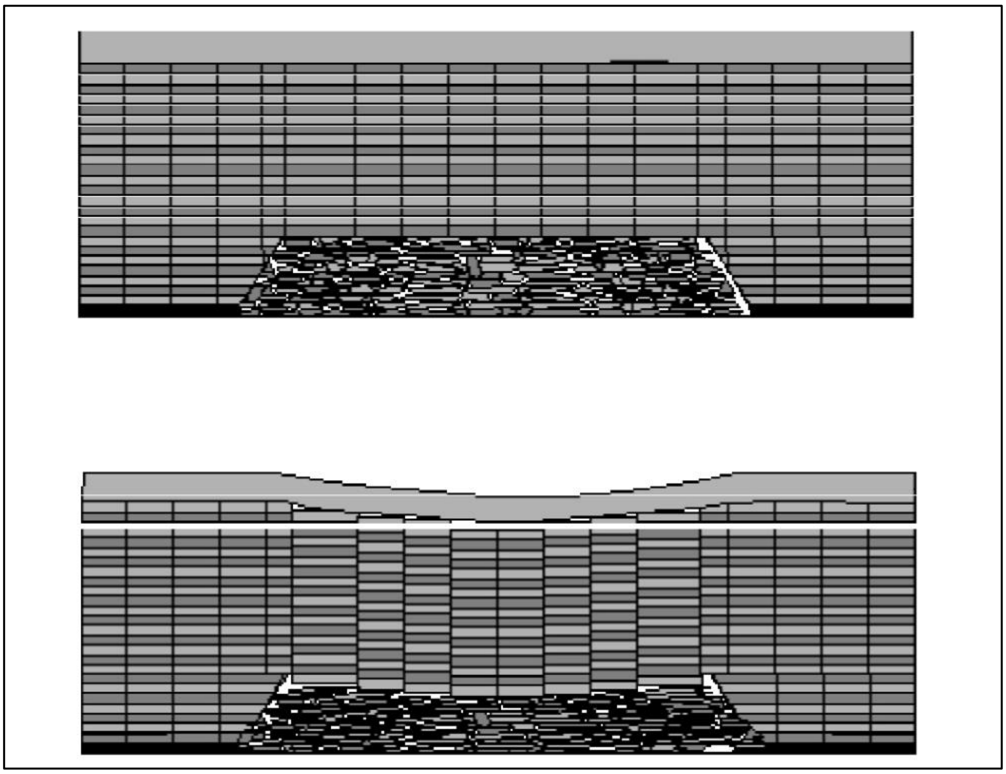


Figure 2.3: Simplified illustration of the subsidence process (Canbulat et al., 2020)

Subsidence shown in Figure 2.3, clearly indicates the effect on the surface and topography. This also gives a clear understanding that any subsidence at any depth in the reshaped spoil area has an effect on the surface. However, it is also recognised that subsidence that occurs deeper in the profile will have less impact at the surface than subsidence that is closer to the surface.

While topography is less affected in lower rainfall areas and where drainage is sufficient, this will not be the same in high rainfall areas. Combined with compaction, subsidence can result in “swampy or marshy” surface areas where infiltration and drainage are impeded. This will significantly reduce the potential of arable land (LaRSSA, 2019). During the rainy season, seasonally perched water tables may form.

Erosion is another concern associated with subsidence and its effect on topography. Depression areas on the surface (also called melon holes) formed due to soil subsidence, creates a water catchment area that promotes ponding. Surface water accumulates in the depression area, resulting in waterlogging. Perched water tables can reach the surface and result in overland flow from depression areas, developing erosion risks. Another problem with these perched water tables is the risk of equipment being damaged and getting stuck, especially when the area is used as arable land.

4. Coal mine impacted water

Large volumes of mine-impacted water are produced in South Africa (Tanner et al., 1999). Mining has an impact on the natural water environment throughout the mining life cycle, and even long after mine closure, water can still be impacted (Annandale et al., 2009). In a water-scarce country that is classified as arid to semi-arid, all measures must be taken to preserve water quality and to ensure that the already scarce resource is not adversely affected (Annandale et al., 2006; Jovanovic et al., 1998).

Different qualities of water emanate from coal mines. The quality is mostly dependent on the geological properties of the coal and the material the water comes in contact with. High concentrations of salts render some waters unsuitable for discharge to the environment without first being treated (Jovanovic et al., 2002). Not all mine water is acidic, there are cases where mine-impacted waters are circum-neutral, even without being treated. The problem is that the water is saline, often dominated by calcium and magnesium sulphate, which can be a potential pollution problem for the environment. However, studies on coal mine water have shown that there is a potential use for such waters for crop irrigation (Jovanovic et al., 1998; Annandale et al., 2001; Annandale et al., 2006). The end product is a pH-neutral (circum-neutral) water with a high calcium sulphate content (Annandale et al., 2002). This is also referred to as “gypsiferous mine water”.

4.1 Irrigation with coal mine water

Disposal of mine water is a global problem (Pulles et al., 1995). Gypsiferous mine water can be a significant problem or a potential asset. Large amounts of water can be utilized as a possible source for irrigation in the farming community, especially in the Highveld in Mpumalanga. As previously mentioned, the coalfields in Mpumalanga underlie some of the highest potential arable lands. Water resources for irrigation are already under pressure in this area. The surplus water problem for many mines can be significantly reduced through irrigation, and this will also be beneficial for the farming sector.

Du Plessis, (1983), was the first to evaluate the potential use of gypsiferous mine water for irrigation in South Africa. Large amounts of mine water can be used for irrigation in the Highveld of Mpumalanga. Environmental pollution will be reduced, as some salts in the water will precipitate in the soil as gypsum, therefore being removed from the water system (Annandale et al., 2001; Jovanovic et al., 2002). As much as 70% of salts contained in mine waters can be removed in this way and the soils are not negatively affected (Du Plessis, 1983). Contamination of downstream water sources could also be reduced by precipitation of salts in the irrigated soil. Since the late ’90s, several trials of irrigation with gypsiferous water on a commercial scale were done in eMalahleni, Mpumalanga (Annandale et al., 2001; Jovanovic et al., 1998). Higher crop yields were obtained under gypsiferous mine water irrigation compared to dryland farming (Annandale et al., 2006). Irrigating arable land and producing crops can also assist with the high treatment cost of contaminated mine water. This will also reduce the surplus water problem for many mines.

Annandale et al., 2006 reported possible nutrient deficiencies occurring due to high levels of Ca and SO_4 dominating the system, but this is easily manageable through correct fertilization. Using the soil water balance (SWB) model, long-term simulations were done to assess the effect of gypsiferous mine water irrigation on soil and groundwater resources. Annandale et al., 1999 concluded that irrigation with gypsiferous mine water should not cause irreparable damage to the soil and groundwater.

Gypsiferous mine water irrigation could be feasible if properly managed and monitored. Knowledge of soil properties is critical for the sustainability and success of irrigation with these waters.

4.2 Irrigation on rehabilitated profiles

The amount of rehabilitated land available is increasing year by year. More than 75 000 hectares were rehabilitated in Mpumalanga by 2008. This includes the physical rehabilitated areas where the soil was disturbed and also the surrounding area where the operations took place (Vermeulen et al., 2008). Not all of the 75 000 ha is suitable for possible farming or irrigation, but a significant amount was classified as high-potential arable land before mining commenced. The size of the opportunity depends on the availability of suitable irrigable soils in close proximity to mine waters (Tanner et al., 1999). This signifies the importance of good rehabilitation practices to create the opportunity for irrigation on rehabilitated soil. Another key reason why mine water irrigation on rehabilitated profiles is investigated is because of the potential for mine water drainage through the rehabilitated profile to be stored within the “basin” left after the coal has been extracted, thus providing an additional barrier to mine water drainage entering the adjacent clean water systems (rivers, streams etc).

Managing irrigation on rehabilitated soils requires particular attention and knowledge of every area that is considered for irrigation. The suitability of soils for irrigation on rehabilitated sites is determined by mainly two factors. According to Vermeulen & Usher, (2009), these influential factors are the topsoil and spoil underneath. The requirements for the suitability of soil for irrigation considered in this study were derived from Vermeulen et al., 2008 and SABI (South African Irrigation Institute). The final topography of rehabilitated land, however, was not discussed in detail, and is expected to be a key factor in determining the suitability of soil for irrigation.

The depth and type of the topsoil are crucial for determining the suitability for irrigation. The infiltration rate of the soil must be sufficient to prevent run off when small amounts of rainfall occur. The soil texture, slope and surface play a significant part in the infiltrability of the soil. Secondly, good internal drainage is necessary for irrigable soil. Good internal drainage allows the water to move freely through the root zone to prevent waterlogging. Restricting layers in the soil, whether brought about through compaction or with the inherent nature of duplex soils, have a great impact on internal drainage. Thirdly, sub surface drainage is important for excess water to leave the system. This also allows leaching in the profile that is necessary, otherwise soil is prone to salt accumulation (Vermeulen & Usher, 2009). Lastly, water-holding capacity (WHC) is a factor that determines the suitability of soils for irrigation. In some cases, a lower WHC has the ability of being able to replenish water used frequently, something that can be done with irrigation.

The second factor that irrigation on rehabilitated soil depends on is the spoil underneath the soil. Pre-mining EIAs should have assessed the mine overburden when identifying the requirements for correct rehabilitation and post-rehabilitation management. Underlying material can be determined by digging trenches into the spoil. This will assist in determining infiltration and drainage capabilities of the profile. The soil layer on top of the spoil is preferably more than 120 cm, in this case, any soil preparation done will not reach the spoil layer and will remain unchanged. A free-draining spoil is preferred and a key feature is the permeability of the soil/spoil interface which, if compact, may be a restricting layer.

The current guidelines for the rehabilitation of coal mines do not include a specific section where the focus is on rehabilitating to an irrigable standard. With the possible opportunity to irrigate with mine water which is mainly in close proximity to rehabilitated land, guidelines for rehabilitating land to irrigable potential will be a valuable addition to the existing standards. Whether they are effective will depend on the degree to which the guidelines are followed by the mining companies.

5. Current trial of gypsiferous mine water irrigation

In 2016, a demonstration trial commenced that is still ongoing, where untreated, circum-neutral void water is used for irrigation in Mpumalanga. The aims of the mine water irrigation study are to monitor water and salt balances for a commercial scale mine water irrigation scheme to monitor and predict the sustainability and long-term impact of gypsiferous mine water irrigation. A report on this field study is published annually and presented to the WRC (report no. TT 855-1-21). The field trial is at Mafube Colliery in Mpumalanga, which is also where the irrigated rehabilitated site is situated where the research was done for this study. More detail on the rehabilitated site is presented in Chapter 4. Figure 2.4 shows irrigation pivots on the unmined and rehabilitated land and going will be referred to as the unmined pivot and rehabilitated pivot going forward.

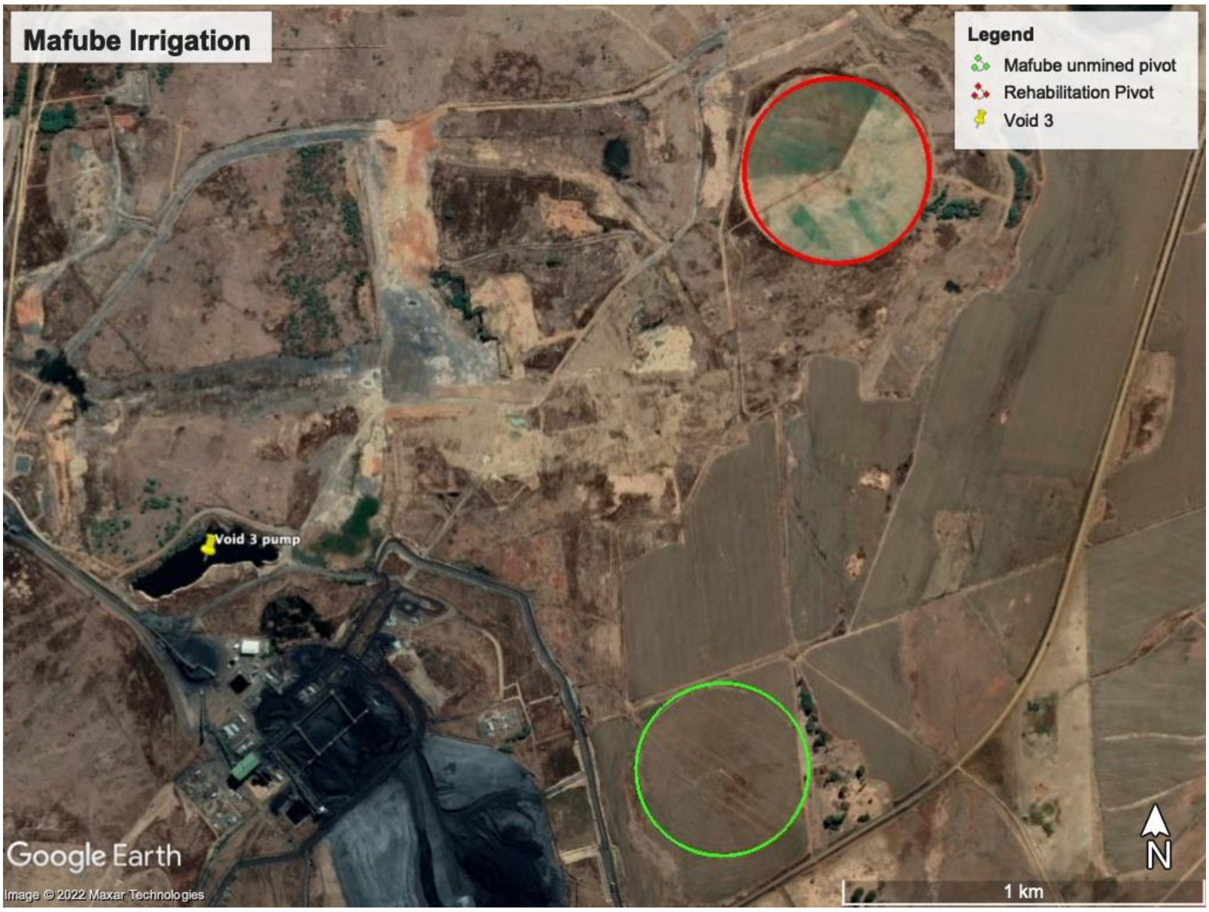


Figure 2.4: Irrigation water source, unmined Mafube pivot and Rehabilitation pivot.

The Mafube unmined pivot demonstrated a cost-effective and productive method of utilizing untreated circum-neutral mine water. No negative impact on the soil or groundwater was recorded for the short term and has been demonstrated to be sustainable (WRC report no. TT 855-1-21).

The work done in this study of irrigating on rehabilitated land is part of a bigger project of irrigation with mine water, and can be a possible solution for mine water and rehabilitation problems. This study focussed on the variability of rehabilitated land, the effect of rehabilitated soil properties on crop growth, the irrigable potential of rehabilitated land and the effect of irrigation with circum-neutral mine water on rehabilitated land.

Chapter 3: Mine water quality and suitability for irrigation

Utilizing mine water as a source of irrigation water has been researched for a long time. A seven-year trial is still underway where mine water from Mafube is used for irrigation on unmined land. This has proven to be both productive and profitable, and the effects on surrounding water sources and soil are not noticeable at this stage. Reports on this trial are available from the WRC. Report no. TT 885-1-21 is the most recent report from the WRC containing this project's data and results.

There are three important aspects that need to be identified and considered before any irrigation developments are initiated. Firstly, the mine must have a constant positive water balance. This is crucial as the general concept behind mine-water irrigation is that it is a sustainable and efficient method to utilize excessive mine water and reduce treatment practices. If the mine does not have a positive water balance and water availability for irrigation is constantly disrupted, irrigation with mine water will not be a sustainable solution. Secondly, the water quality must be suitable for irrigation purposes. This includes the effect on crop production and soil properties over the long term. Thirdly, there must be irrigable soils in the surrounding area.

Sustainability over the long term is an important aspect when irrigating with mine water, therefore, modelling is a useful and necessary tool to determine the suitability of the mine water. The Decision Support System (DSS) is a recently developed irrigation water quality assessment model, that makes use of soil-water balance (SWB) model simulations to predict long-term water and salt balances of site-specific scenarios.
The objective of this chapter is to determine if the mine water from Mafube is suitable for irrigation on selected crops.

3.1 Mine water quality

Circum-neutral water can be defined as water with a nearly neutral pH, usually between 6.5 and 8 (Vriens et al., 2019). Table 3.1 represents the average water quality from 2016 to 2022. From the data in Table 3.1, the pH varies between 7.5 and 8.1, therefore, the mine water at Mafube can be classified as circum-neutral. The source of the irrigation water is Void 3 at Mafube. Figure 3.1 shows Void 3 and the rehabilitated area. Every fortnight water is sampled by Mafube and analysed by a professional laboratory. Water quality does vary throughout the year, most likely due to rainfall and operational use from the mine. Water from Void 3 is untreated as the pH indicates no risk of acidity or acid mine drainage (AMD) being produced.

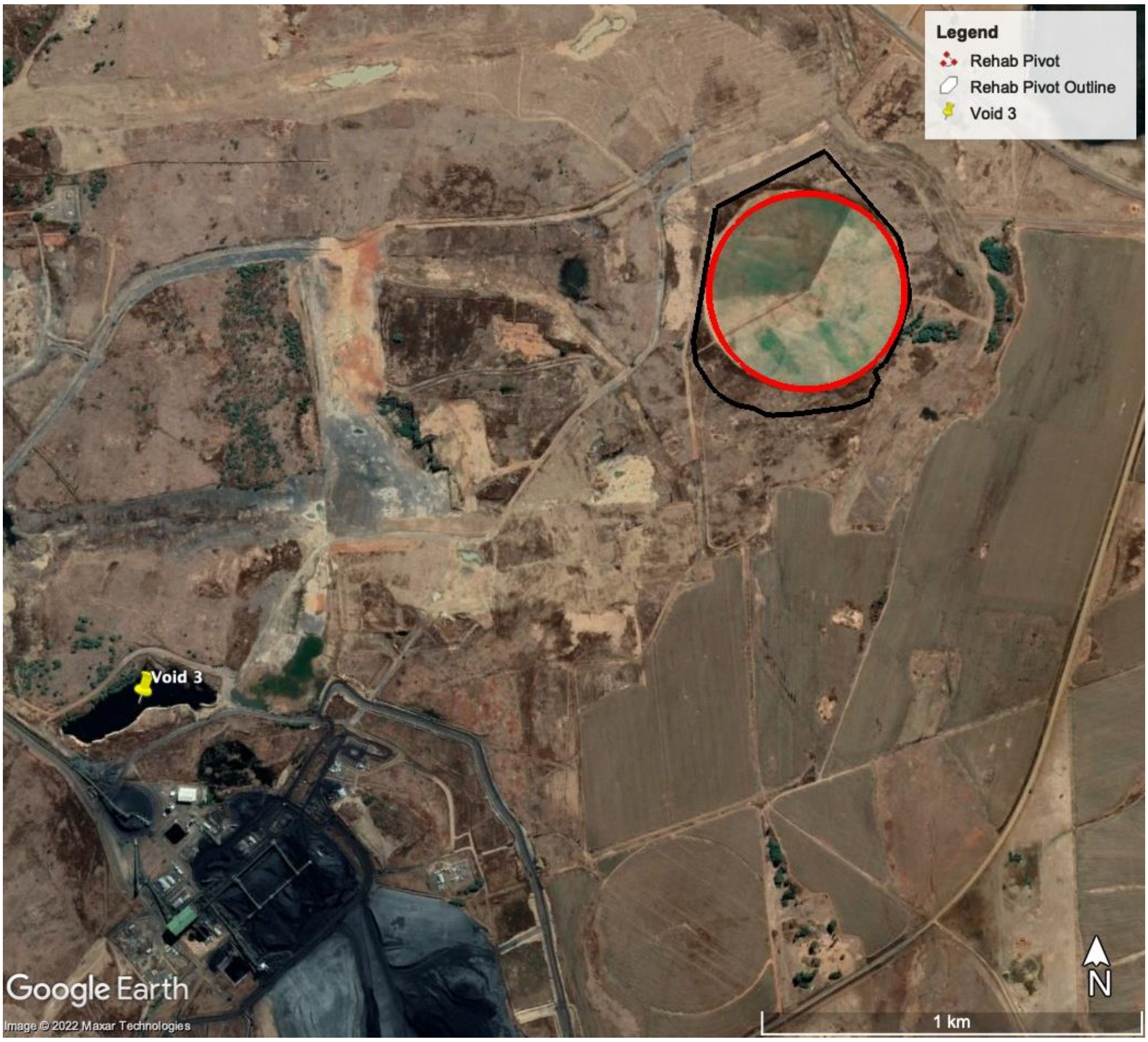


Figure 3.1: Void 3 and the Rehabilitated irrigation Field at Mafube Colliery.

Mine water in Mpumalanga tends to be gypsiferous, being high in calcium and sulphate ions (Annandale et al., 2006). Water quality data presented in a table can be misleading if not properly prepared and presented, for this reason a Piper diagram is very useful in easily identifying the type of water. Figure 3.2 indicates a Piper diagram representing the water qualities from Table 3.1.

Table 3.1: Average water quality for Void 3 from 2017 to 2022

	Variable	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Average**	**STDEV**
mg/L	**pH**	7,7	8,0	8,1	8,0	8,1	8,3	8,0	0,2
	EC (mS/m)	224	217	271	423	426	386	324	98
	Ca	257	281	267	342	350	358	309	46
	Mg	164	162	127	229	214	175	179	37
	Na	59	57	69	99	92	71	75	17
	K	32	34	35	28	37	35	34	3
	$CaCO3$	224	245	191	140	193	183	196	36
	$C\ell^-$	22	23	23	23	25	18	22	2
	SO_4^{2-}	1197	1055	1049	1926	2063	1672	1494	452
	P	2,2	0,4	0,4	0,2	1,2	0,2	0,8	0,82
	F^-	0,5	0,4	0,8	0,7	0,8	0,4	0,6	0,18
	N	1,3	1	0,5	0,4	0,5	0,6	0,7	0,35
	$A\ell$	0,2	0,8	0,8	0,2	0,1	0,2	0,4	0,33
	Fe	2,9	1,2	0,0	0,1	0,1	0,1	0,8	1,14
	Mn	0,8	1	1,5	0,7	0,9	0,2	0,8	0,43
	Zn	0,1	0,1	0,1	1,2	0,0	0,1	0,3	0,45
	Suspended solids	65	10	40	109	51	157	72	53

Water quality is converted from mg/l to %meq/l, as it is the input required for the piper diagram. As some of the constituents in Table 3.1 vary between years, the piper diagram indicates that these variations have a minimal influence on the nature of the water signature.

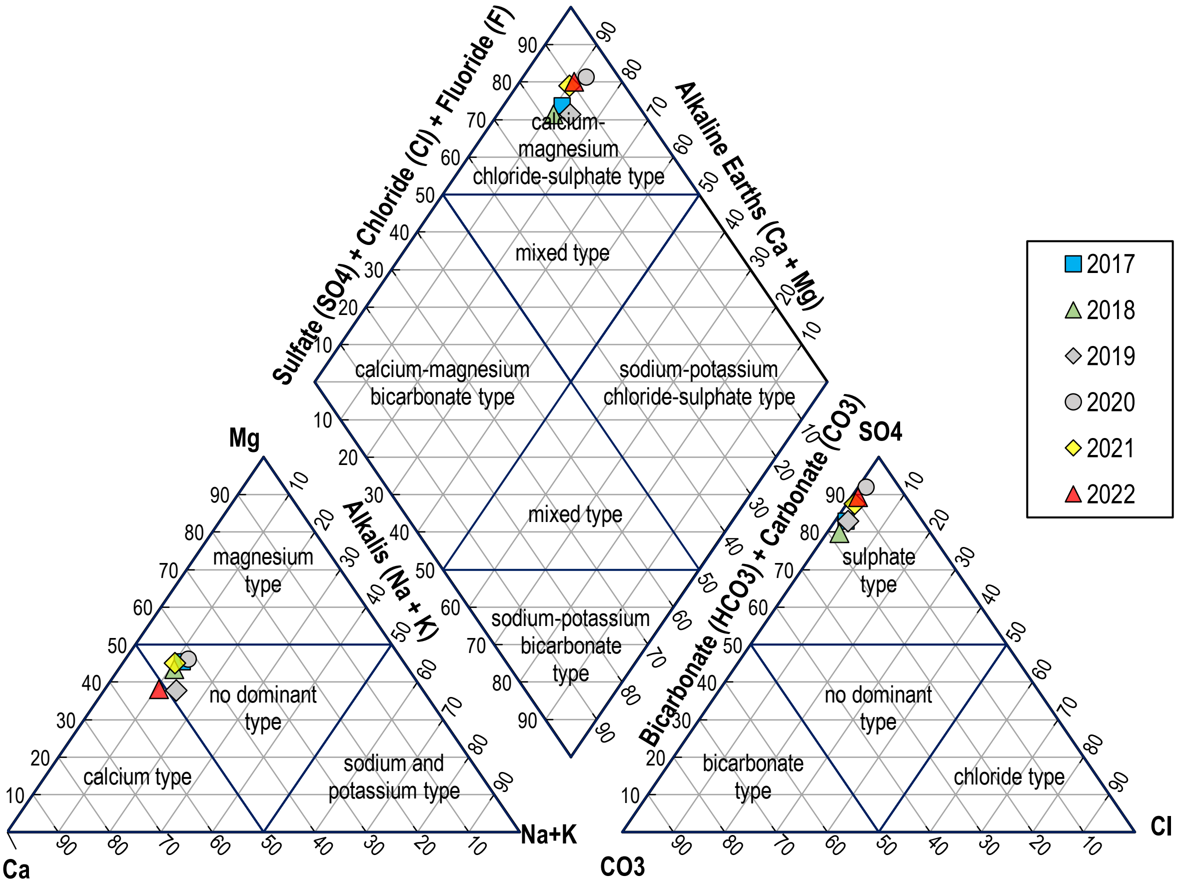


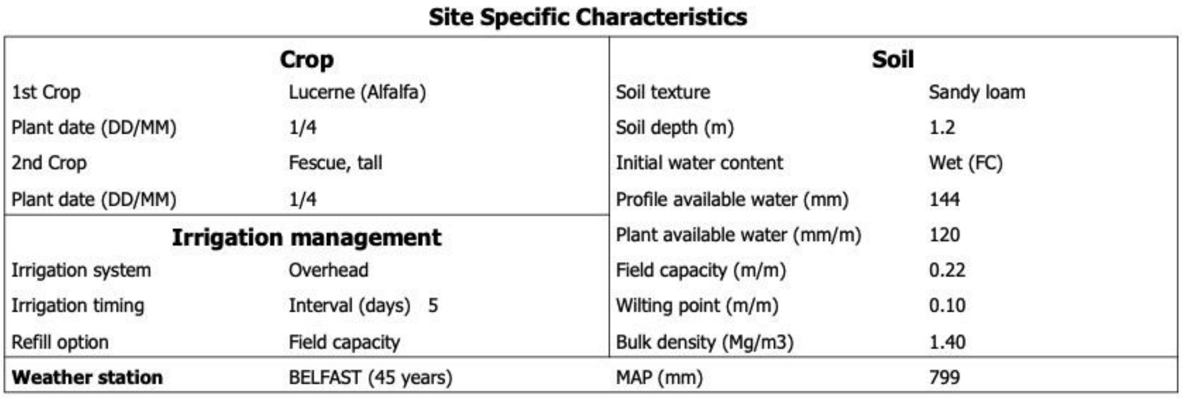
Figure 3.2: Piper diagram representing the water type for Void 3 from 2016- 2022.

From the Piper diagram, it can be concluded that the water from void 3 at Mafube can be classified as calcium-magnesium sulphate type as sulphate dominates chloride and bicarbonate. For four of the six years, calcium and magnesium show equal dominance in the piper diagram, therefore the water is classified as having a calcium-magnesium dominated signature. Water qualities from 2022 in the Piper diagram are classified as calcium dominated, also known as gypsiferous waters. Using a piper diagram for water identification is an easy and helpful method and also useful to see how different concentrations of constituents will affect the outcome.

3.2 Modelling the long-term effect of irrigation with gypsiferous mine water

The DSS is a risk-based model that allows different water qualities to be assessed for their fitness for use (FFU) when irrigated on a wide range of crops (Annandale et al., 2018; du Plessis et al., 2017). It is used to analyse the effect of water on soil, crops and irrigation equipment. The guidelines created consist of 2 tiers: Tier 1 and Tier 2. Tier 1 provides a conservative, generic assessment of the FFU of a given water, thus providing a general idea of whether the water is suitable for irrigation or not. Tier 2 simulations are more site-specific (soil, weather and crop). More details on how the DSS operates can be found in the technical guidelines of the risk-based, site-specific, irrigation water quality guidelines (du Plessis et al., 2017).

The average for the water qualities from 2017-2022, presented in Table 3.1, was used as water quality input to the DSS. Site-specific characteristics consisted of a lucerne-fescue crop rotation, with more details regarding crop selection discussed in Chapter 7. The weather station at Belfast was selected and a simulation period of 45 years was used. Figure 3.3 shows the site-specific characteristics used for the simulation.

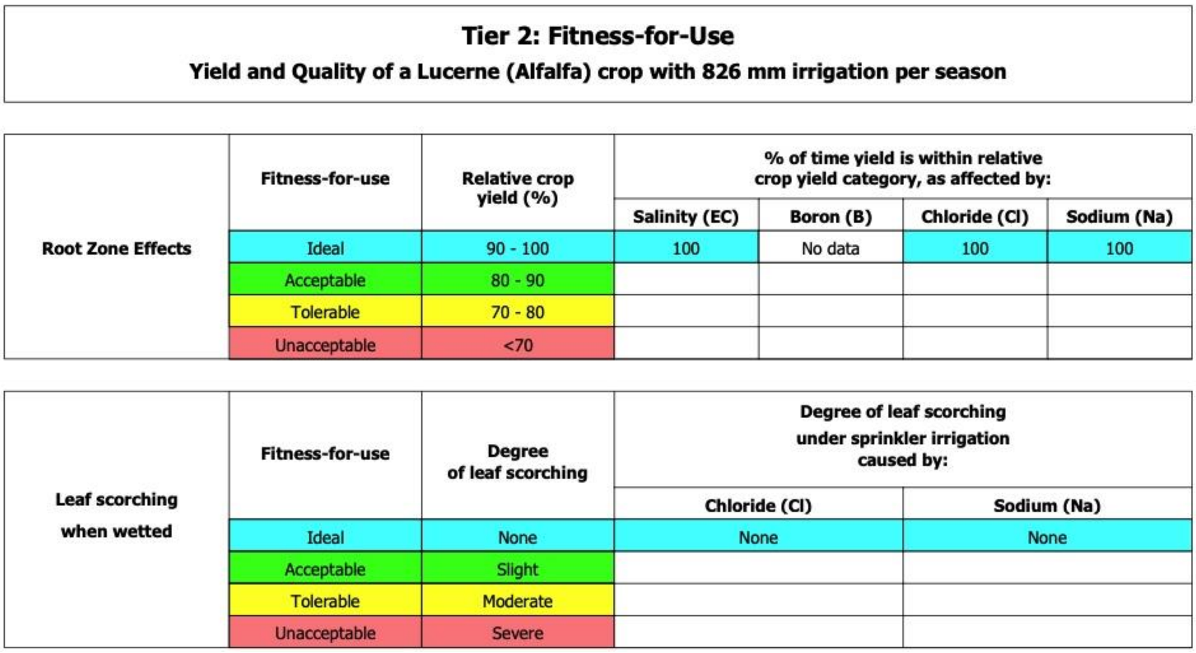


Site Specific Characteristics

Crop		**Soil**	
1st Crop	Lucerne (Alfalfa)	Soil texture	Sandy loam
Plant date (DD/MM)	1/4	Soil depth (m)	1.2
2nd Crop	Fescue, tall	Initial water content	Wet (FC)
Plant date (DD/MM)	1/4	Profile available water (mm)	144
Irrigation management		Plant available water (mm/m)	120
Irrigation system	Overhead	Field capacity (m/m)	0.22
Irrigation timing	Interval (days) 5	Wilting point (m/m)	0.10
Refill option	Field capacity	Bulk density (Mg/m3)	1.40
Weather station	BELFAST (45 years)	MAP (mm)	799

Figure 3.3: Site-specific input for simulation.

Lucerne (Alfalfa) is a much more sensitive crop than fescue, especially for salinity. Figure 3.4 shows the results from the simulation for lucerne when irrigated with mine water. The results indicate ideal conditions for lucerne with no concerns around yield limitations due to irrigation water constituents.



Tier 2: Fitness-for-Use

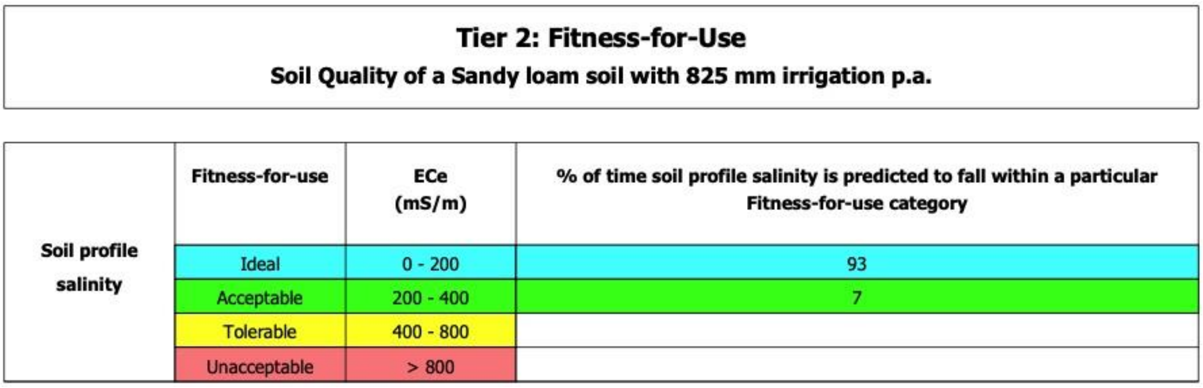
Yield and Quality of a Lucerne (Alfalfa) crop with 826 mm irrigation per season

	Fitness-for-use	**Relative crop yield (%)**	**% of time yield is within relative crop yield category, as affected by:**			
			Salinity (EC)	**Boron (B)**	**Chloride (Cl)**	**Sodium (Na)**
Root Zone Effects	Ideal	90 - 100	100	No data	100	100
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

	Fitness-for-use	**Degree of leaf scorching**	**Degree of leaf scorching under sprinkler irrigation caused by:**	
			Chloride (Cl)	**Sodium (Na)**
Leaf scorching when wetted	Ideal	None	None	None
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

Figure 3.4: Results from the DSS for lucerne.

Soil salinity in the profile was predicted by the model to be ideal for 93% and acceptable for 7% of the time. This shows promising results for using the mine water from Void 3 for irrigation. Figure 3.5 represents the predicted soil profile salinity from the DSS.

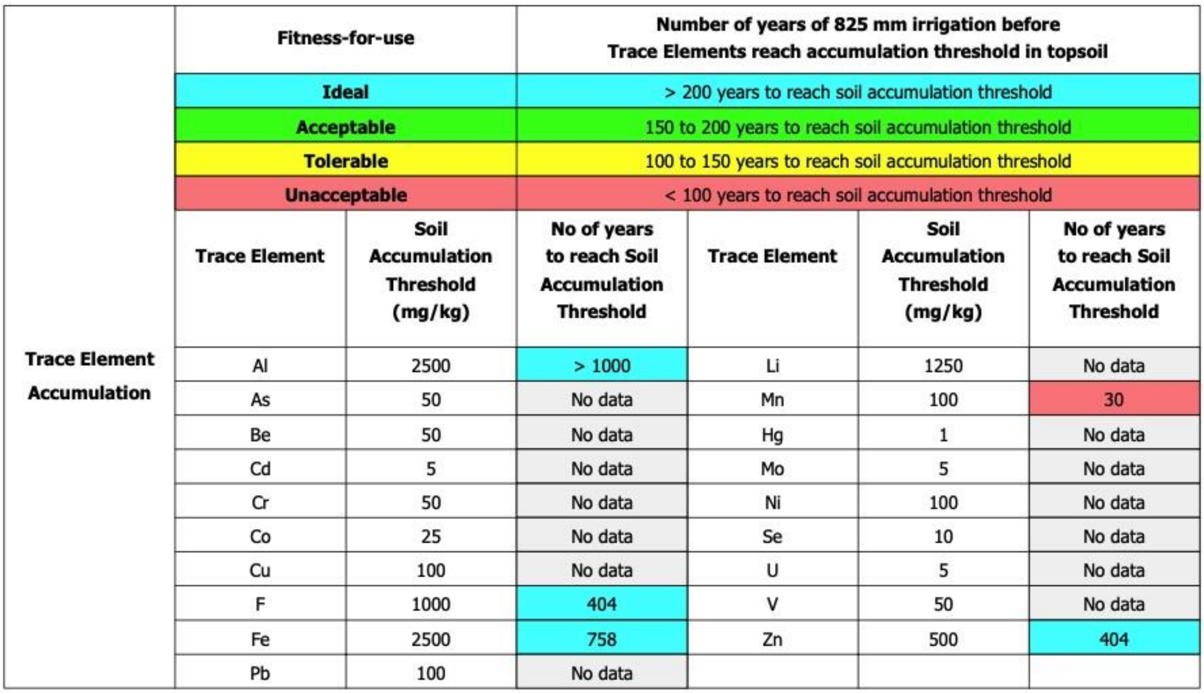


Tier 2: Fitness-for-Use
Soil Quality of a Sandy loam soil with 825 mm irrigation p.a.

	Fitness-for-use	ECe (mS/m)	% of time soil profile salinity is predicted to fall within a particular Fitness-for-use category
Soil profile salinity	Ideal	0 - 200	93
	Acceptable	200 - 400	7
	Tolerable	400 - 800	
	Unacceptable	> 800	

Figure 3.5: Soil profile salinity.

Trace elements are important and can easily influence the suitability of the water for irrigation. The accumulation of manganese in the soil was shown to reach the internationally published soil threshold level only after 30 years of irrigating with 825 mm of mine water annually. Manganese in the water and accumulation in the soil should be closely monitored. Figure 3.6 shows the expected time to reach trace element thresholds in the soil profile.



	Fitness-for-use		Number of years of 825 mm irrigation before Trace Elements reach accumulation threshold in topsoil			
	Ideal		> 200 years to reach soil accumulation threshold			
	Acceptable		150 to 200 years to reach soil accumulation threshold			
	Tolerable		100 to 150 years to reach soil accumulation threshold			
	Unacceptable		< 100 years to reach soil accumulation threshold			
	Trace Element	**Soil Accumulation Threshold (mg/kg)**	**No of years to reach Soil Accumulation Threshold**	**Trace Element**	**Soil Accumulation Threshold (mg/kg)**	**No of years to reach Soil Accumulation Threshold**
Trace Element Accumulation	Al	2500	> 1000	Li	1250	No data
	As	50	No data	Mn	100	30
	Be	50	No data	Hg	1	No data
	Cd	5	No data	Mo	5	No data
	Cr	50	No data	Ni	100	No data
	Co	25	No data	Se	10	No data
	Cu	100	No data	U	5	No data
	F	1000	404	V	50	No data
	Fe	2500	758	Zn	500	404
	Pb	100	No data			

Figure 3.6: Trace element accumulation in the soil profile.

Except for manganese, no other elements were highlighted as being of any potential concern. Under well drained soil conditions, which are essential for successful irrigation, manganese levels are not expected to be excessive. The complete details and results of the simulation are attached in Appendix A.

3.3 Irrigation with mine water on rehabilitated land

As seen in Figure 3.2, the mine water for 2022 was identified as gypsiferous. This section covers the 2022 irrigation season at the rehabilitated pivot. Results presented in this section will serve as the initial data going forward for monitoring the effect of circum-neutral mine water irrigation on rehabilitated land. Figure 3.7 shows the soil sampling locations from 2021 before any irrigation commenced. This will most likely be the reference for future locations for soil samples at the Rehabilitation Pivot.

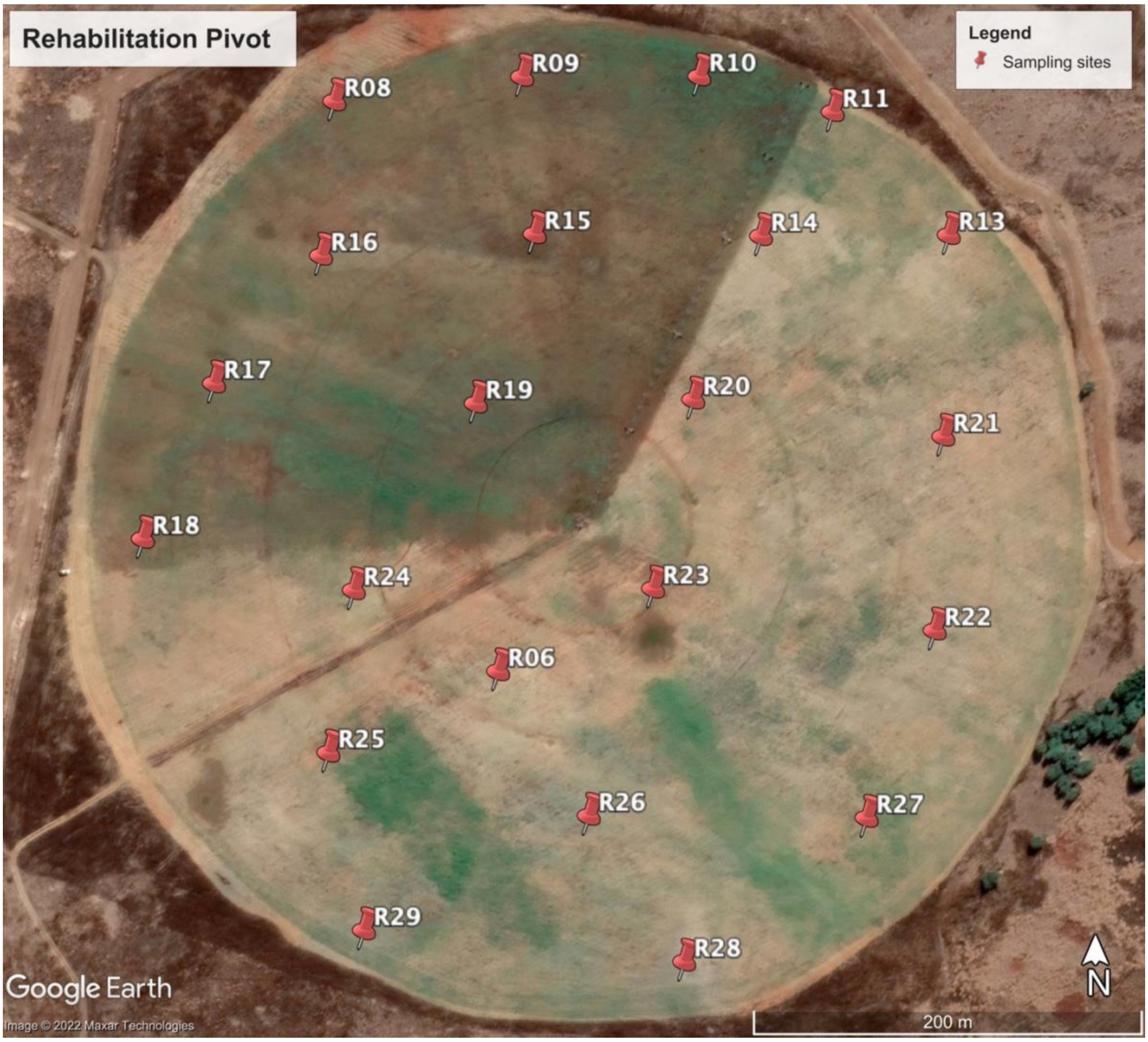


Figure 3.7: Initial soil sampling locations at the Rehabilitation Field.

The soil samples from 2021 were analysed using the Mehlich-3 method, and for consistency, the same method was used for the 2022 samples. However, only a small amount of irrigation was applied during 2022 and very small changes, if any, were expected in soil constituents.

Crop establishment at the rehabilitated site is explained and discussed in Chapter 7. Section 3.3 focuses on the irrigation with gypsiferous mine water and the impact on rehabilitated land.

Irrigation started in May 2022 after the heavy rain throughout April. Figure 3.8 represents the cumulative rainfall and irrigation separately at the rehabilitated land from the start of the season in a graph and Table 3.2 represents the monthly rainfall and irrigation from April 2022 to December 13, 2022.

Table 3.2: Monthly rainfall and irrigation at the Rehabilitation Pivot from April until 13 December 2022

Date	**Rain**	**Irrigation**
	mm	**mm**
April	144	0
May	20	17,5
June	0	19,3
July	5	30,2
August	0	67,3
September	15	0
October	67	18
November	130	6,9
December	62	0
Total	**443**	**159,2**

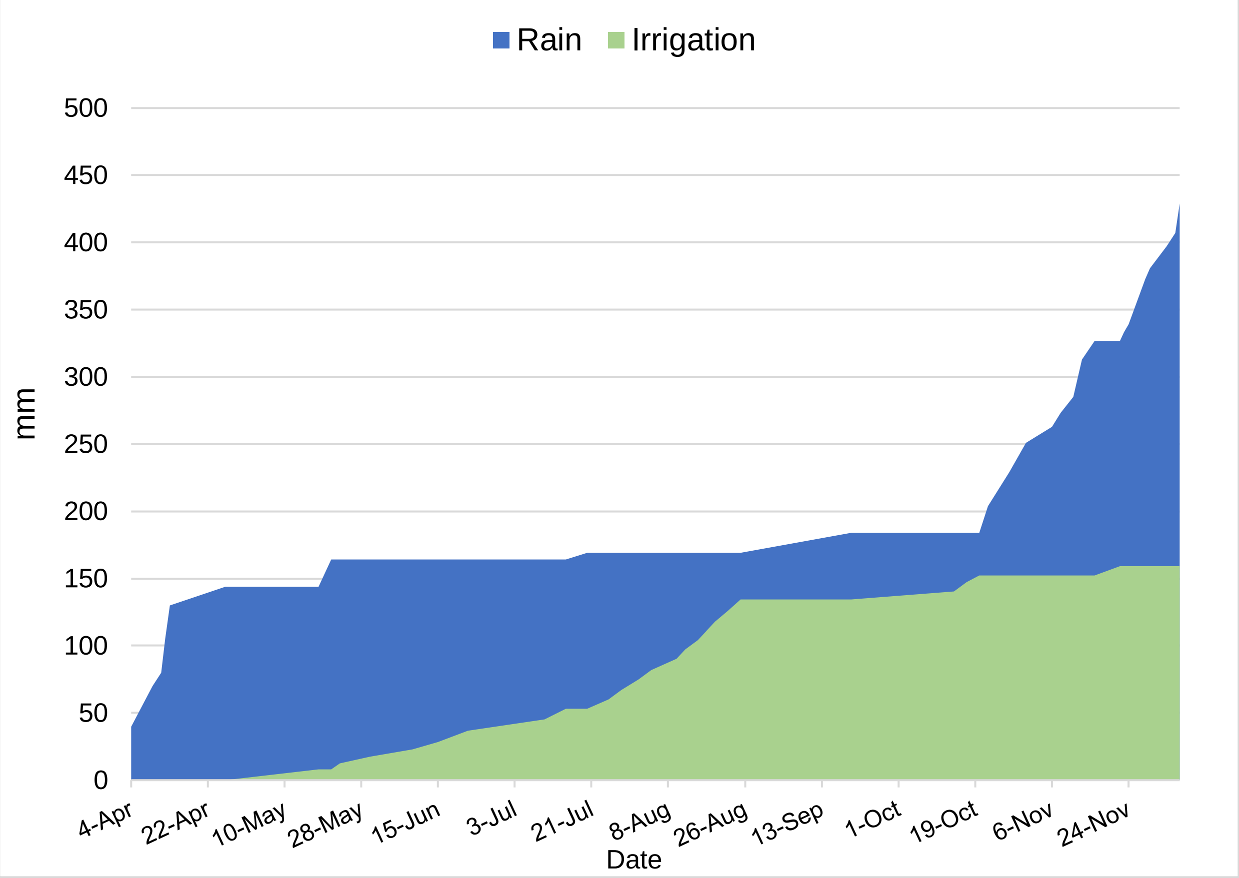


Figure 3.8: Cumulative rainfall and irrigation from April 2022 at the Rehabilitation Field.

Approximately 140 mm of rain was recorded in the first three weeks of April 2022. The effect of this heavy rain on crops and rehabilitated land are discussed in Chapter 7.

Table 3.3 shows the salts applied during the irrigation period. Mine water quality slightly changes during the dry winter months when rainfall is negligible, and salt concentration is higher due to less dilution than is present in the wet summer months. Salinity levels in the soil are expected to increase during winter irrigation when rainfall is minimal, but should decrease during the summer rainfall period. Results from the DSS showed that salinity levels in the soil are not expected to reach a critical threshold where crop production is affected or the water is deemed unusable. This indicates sufficient leaching is brought about through rainfall, as irrigations were applied to field capacity, with no deliberate leaching fraction applied.

Table 3.3: Water quality and salts applied during the irrigation period

	Irrigation amount (mm)	**[ ] - mg/L**	**Salts applied kg/ha**	**Salts applied kg/20ha**
Ca	159,2	358	570	11399
Mg		175	279	5572
K		35	56	1114
Na		71	113	2261
Cl		18	29	573
SO_4		1672	2662	53236

Table 3.3 presents a simple indication of the salt applied through the season. Irrigation during the 2022 season was low due to the high rainfall. During the winter and in drier years, the salts applied through irrigation are expected to be much higher.

Table 3.4 presents the salt concentration measured and Table 3.5 presents the trace element concentration in the soil in 2021 before irrigation commenced. The Mehlich-3 extraction method was used for the 2021 soil analyses.

Table 3.4: Mehlich 3 extractable major inorganic cation concentrations measured in the soil in 2021

Site	Ca	Mg	Na	K
	mg/kg	mg/kg	mg/kg	mg/kg
R 02	464	134	11	95
R 04	331	71	11	65
R 05	576	179	11	96
R 06	497	119	12	38
R 07	1218	258	13	129
R 08	188	59	1	55
R 09	745	448	99	128
R 11	579	214	22	96
R 13	384	138	13	70
R 14	515	315	54	76
R 15	570	242	18	100
R 16	290	122	15	34
R 17	411	137	11	51
R 18	481	176	19	47
R 19	819	251	13	147
R 20	369	134	9	101
R 21	468	134	11	64
R 22	519	147	18	55
R 23	311	87	13	31
R 24	457	154	9	83
R 25	616	151	10	62
R 26	849	192	11	152
R 27	579	328	57	77
R 28	631	246	57	78
R 29	552	146	10	90

Table 3.5: Mehlich 3 extractable trace element concentration in soil in 2021

Site	Fe	Mn	Al	Cu	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
R 02	51,6	28,6	508,8	1,7	0,0
R 04	98,9	13,0	609,0	1,9	0,0
R 05	51,0	45,2	760,6	2,9	0,0
R 06	40,8	15,5	562,2	1,7	0,0
R 07	78,5	15,8	508,7	4,0	6,5
R 08	89,5	12,3	546,1	1,3	0,0
R 09	93,7	15,0	588,1	1,3	0,0
R 11	55,5	46,2	511,2	1,9	0,0
R 13	59,3	10,4	619,8	1,7	0,0
R 14	60,8	13,8	549,2	1,7	0,0
R 15	65,9	17,6	616,1	2,6	0,0
R 16	49,4	18,1	681,0	1,6	0,0
R 17	41,9	41,8	583,9	1,9	0,0
R 18	57,9	35,2	539,4	2,1	0,1
R 19	78,2	64,5	487,1	2,3	0,0
R 20	37,0	12,9	686,2	1,8	0,0
R 21	84,0	28,0	587,5	2,2	0,0
R 22	70,6	26,9	604,3	2,1	0,0
R 23	35,2	20,7	691,1	2,0	0,0
R 24	71,6	36,0	543,2	1,9	0,0
R 25	56,6	23,8	605,7	1,9	0,0
R 26	63,4	57,0	567,9	2,2	0,0
R 27	59,3	14,6	547,3	1,7	0,0
R 28	68,0	24,7	552,4	1,8	0,0
R 29	48,2	32,6	542,8	1,7	0,0

Chemical concentrations in the soil are expected to change as fertilizer is applied through the season and nutrient uptake from the crop occurs. Trace element concentrations vary significantly between sampling locations, especially manganese. This indicates high soil variability in the soil, which will be discussed in detail in Chapter 5. Another set of trace element analyses was done in November 2002. Unfortunately, the soil samples taken in November 2022 were contaminated and therefore the integrity of the samples were questioned. Due to this, the analysis of the samples are not included. For future studies on this project, it would be recommended to start with soil samples at the Rehabilitation Pivot at the same sampling locations used for this study.

3.4 Conclusion

The DSS categorised the mine water from void 3 at Mafube as ideal for irrigation purposes with no negative effects expected with the production of lucerne and fescue. The water to be used for irrigation is identified as calcium-magnesium sulphate type water with a circum-neutral pH.

Manganese was the only element of concern for reaching the threshold when water from void 3 is used for irrigation. It is therefore recommended that manganese levels in the soil and water are closely monitored throughout this trial and future projects.

Generally, the water quality is ideal for an irrigation project where mine water is being utilised for irrigation as an alternative method to expensive water treatment. The next chapter consists of the history of the rehabilitated land where the mine water irrigation project is conducted.

Chapter 4: History of the Mafube Rehabilitation site

This chapter provides detail and background on when and where the study was carried out and previous work done on this Rehabilitated Field. This chapter also includes historical images from the rehabilitation area. The rehabilitated site, selected for this trial in 2016, is located in Mpumalanga Province, approximately 2 km NE of Mafube Colliery, 4 km N of the N4 highway, with a longitude of 29°45'59.85"E and latitude of 25°47'30.43"S. The main advantages of this site were its depth of topsoil, close proximity to Void 3 that is used for irrigation, and easy access for the research team, thereby creating a safer working environment than is generally found on an active mine.

4.1 History

Although only limited information was available regarding the historical data for the rehabilitation site at Mafube, satellite images from Google Earth did present some information regarding the timeframe and rehabilitation processes. Unfortunately, from 2010 to 2016 during the mining period, there are no Google earth images available.

Figure 4.1 shows the currently rehabilitated field in 2003 (red circle), before mining commenced. The area was regarded as high-potential agricultural land, with maize the dominant crop produced in this area.

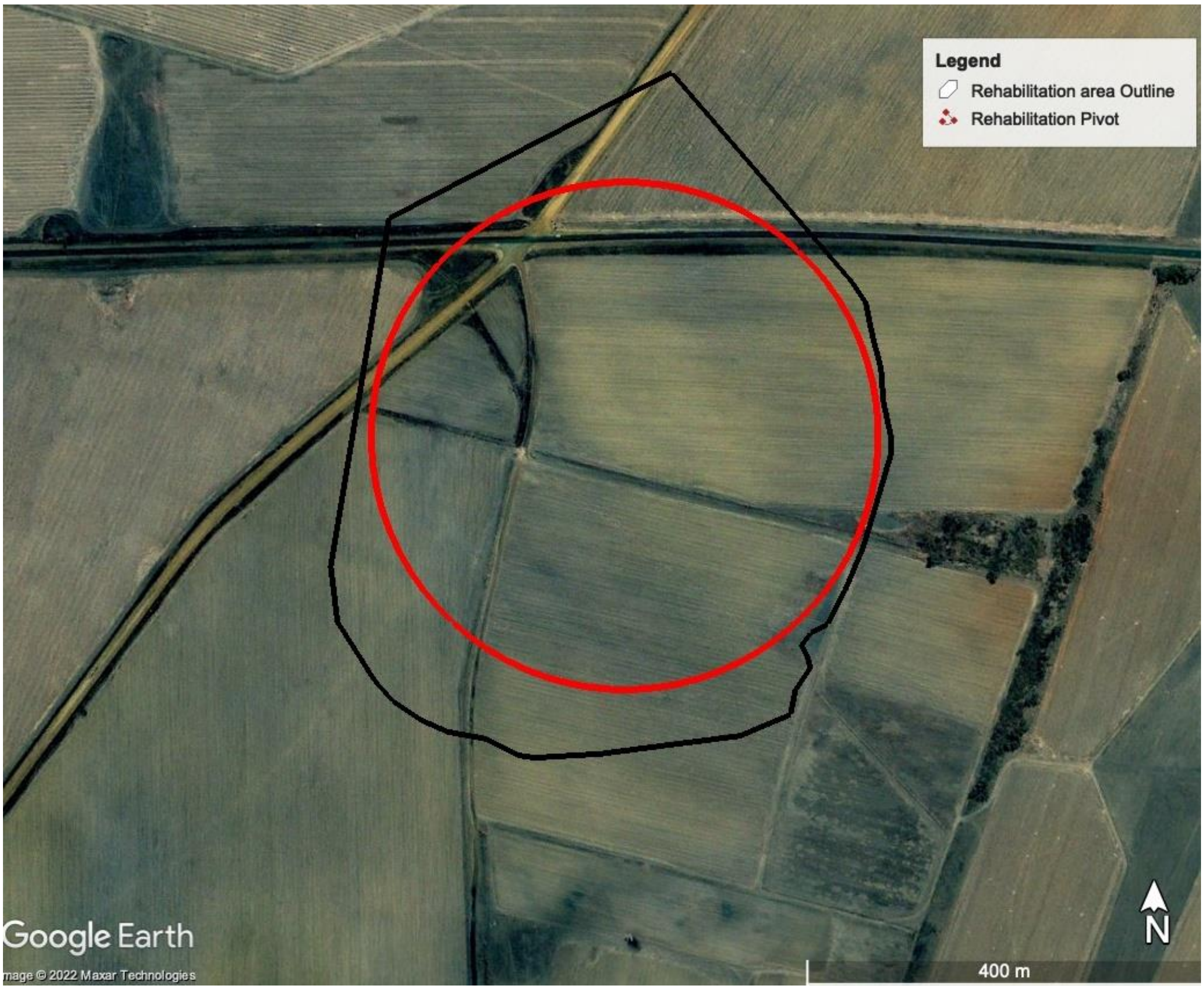


Figure 4.1: Google Earth image representing the current location of the Rehabilitation Pivot in 2003 before mining commenced.

Figure 4.2 shows the same area in 2010 when mining operations were active in the area, the exact date when mining started and the rehabilitation process thereafter is uncertain, but the timeline from Google Earth presents some indication of the timeframe.

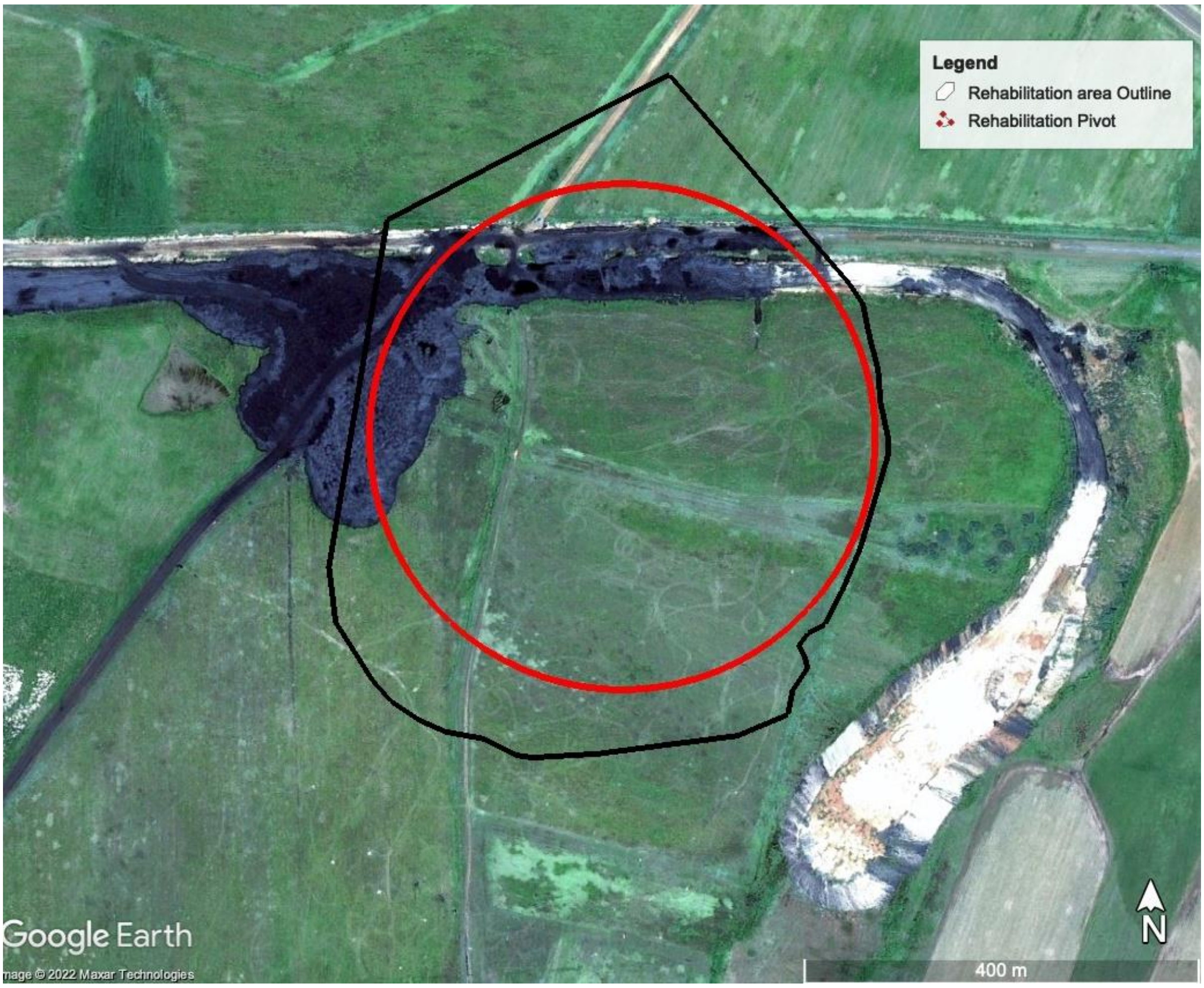


Figure 4.2: Mining operations present at the Rehabilitated Field in 2010.

By 2016, mining in the area was completed, and the rehabilitation process was in the final stages. Figure 4.3 shows the rehabilitation area in 2016 when the rehabilitation process of soil placement was still underway.

Figure 4.3: Rehabilitation Field in 2016.

Figure 4.4 shows the Rehabilitation Field in 2017. Some soil heaps that still needed levelling are visible.

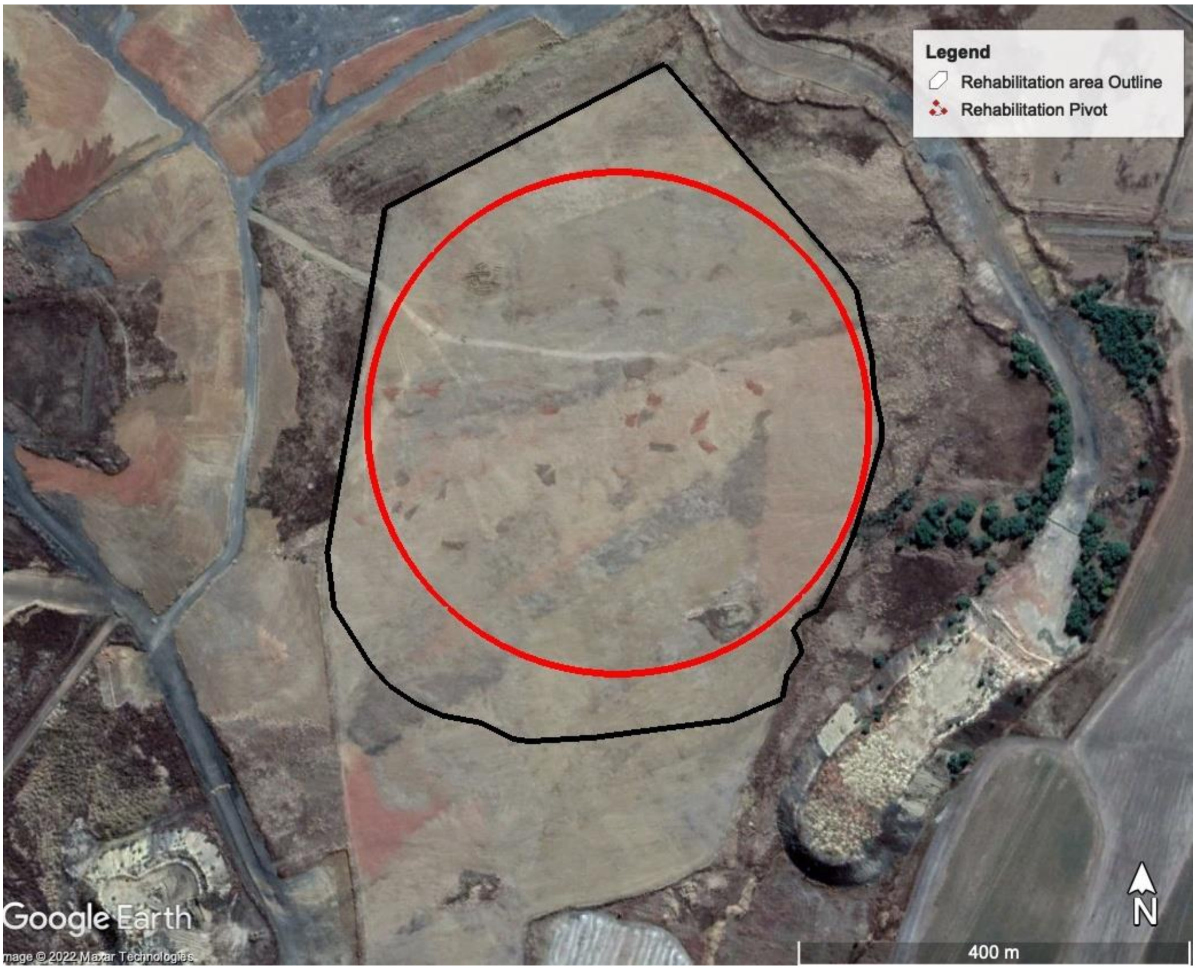


Figure 4.4: Soil heaps visible at the Rehabilitation Field in 2017.

After selecting a suitable site to erect a centre-pivot irrigation system, Mafube Colliery proceeded to procure and commission the assembly of the system. South32 collaborated with this endeavour, by donating an old centre pivot that was not in use at one of their mines. Unfortunately, this pivot was not disassembled correctly, with many bolts and stays just being removed with a cutting torch, causing considerable damage. Costs to refurbish this pivot were considerable, with the farmer responsible for this field estimating that it would have been easier and cheaper to just install a new pivot. There were also delays in establishing the central foundation for this pivot and supplying electricity and water to the site. From the outset of this project, there were problems with insufficient water pressure to the pivot. Figure 4.5 shows the unassembled pivot in 2017 at the rehabilitation site.


Figure 4.5: Unassembled pivot at the Rehabilitation Field.

After the assembly of the pivot, heavy rain fell which resulted in surface ponding of water in several depressions that had developed in the Rehabilitated Field. Figure 4.6 is from January 2019, where heavy water ponding is clearly visible in the north-western part of the pivot.

Suitable stockpiled soil on Mafube was selected with which to fill the depressions. Large volumes of soil were trucked in, in 2019, to fill hollows and reshaping was done with a bulldozer and grader to create a free-draining surface.

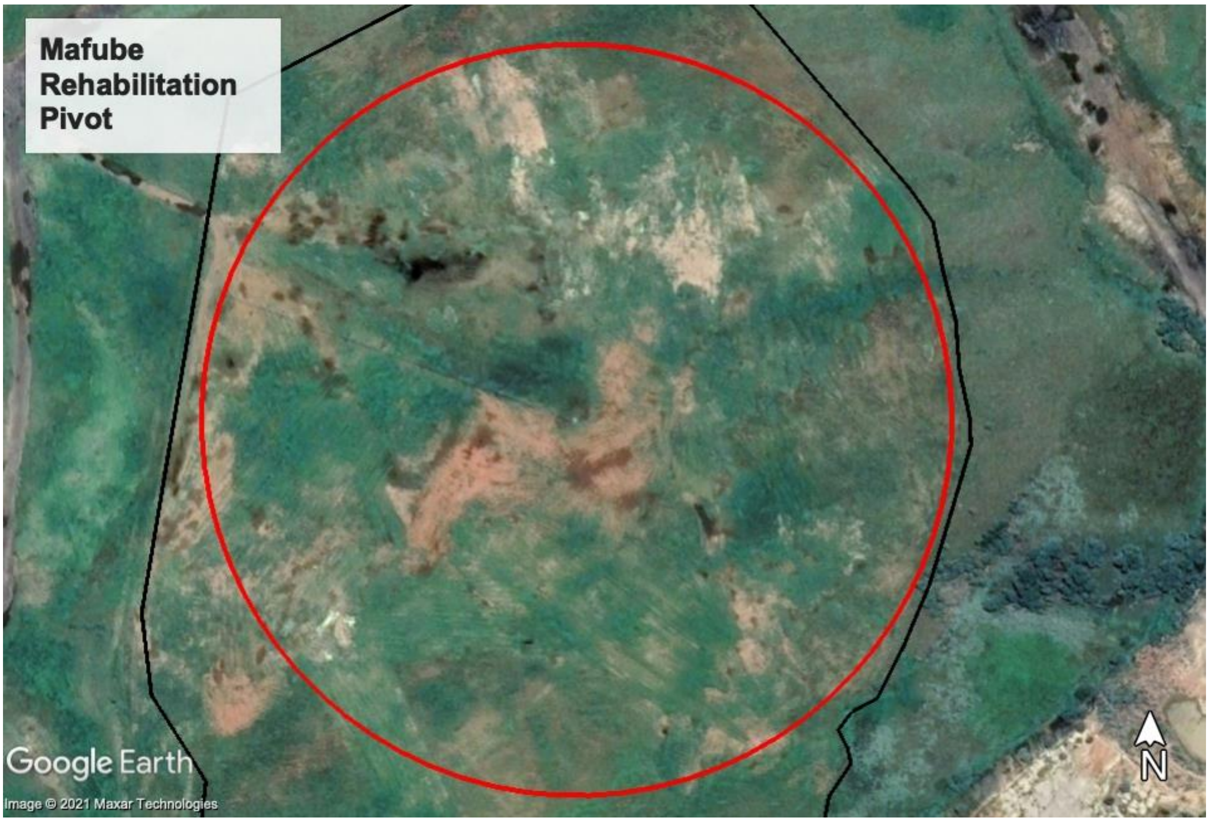


Figure 4.6: Google Earth image from January 2019 with heavy water ponding visible in the north-western part of the pivot.

High variability in soil colour is also visible in Figure 4.6, with the red/brown patches in the centre of the pivot indicating soil that had been recently added to the site. Figures 4.7 and 4.8 present rehabilitation site images from May and July 2019. Heaps of soil that were trucked in to fill the depression that caused the water ponding in Figure 4.6, are visible in Figure 4.7.

Figure 4.7: Google Earth image from May 2019 showing heaps of soil trucked in to fill additional depressions.

The heaps of soil shown in Figure 4.7 were levelled, as can be seen in Figure 4.8. Unfortunately, the additional soil that was trucked in was not of the same quality as the stockpiled soil that was originally selected for this task. The effect of this replaced soil variability is apparent and will be discussed in the chapters that follow.

Figure 4.8: Google Earth image from July 2019 showing the levelled heaps of soil.

Large trucks were used to bring in soil during the rainy season, and this caused severe compaction over some of the rehabilitated areas. Initial efforts to remedy this compaction were undertaken using equipment that was not able to rip deep enough, which resulted in soil disturbance and loosening of only the top 150 to 300 mm of the profile. A bulldozer with better ripping configuration was subsequently hired, which was able to rip in excess of 400 mm. Only half of the pivot area was ripped using this bulldozer due to the start of the next rainy season.

Apart from muddy conditions, the land surface was too uneven for the pivot to safely make a full circle, and the commercial farmer could not plant, as this would have resulted in breakages of his equipment. The unevenness of the field affected the ability of the pivot to run and delayed commissioning of the pivot. Subsequent soil cultivation and preparation for crop production reduced the unevenness to a state where planting and pivot maintenance were possible. Figure 4.9 is the Google Earth image of the Rehabilitation Pivot taken in November 2020.

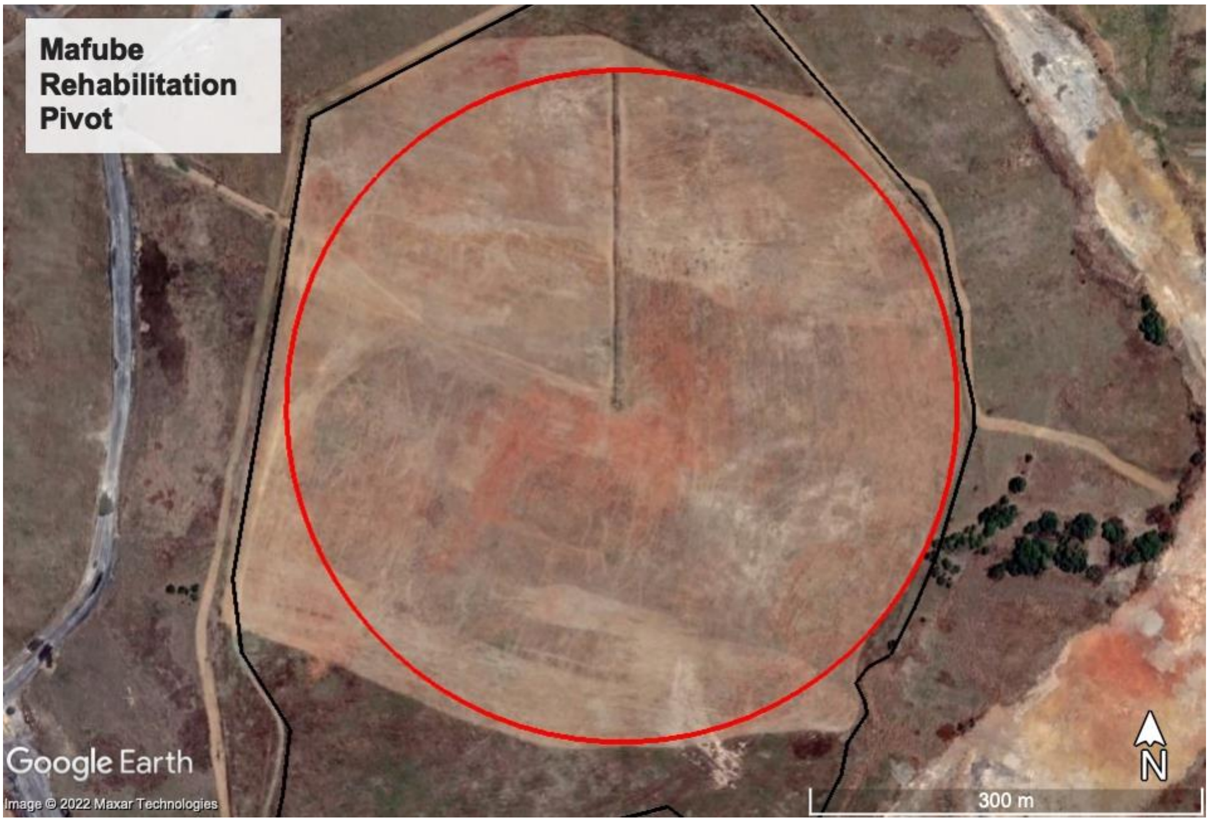


Figure 4.9: Google Earth image from the Rehabilitation Field, November 2020.

Figure 4.10 is from June 2021 when the pivot was fully functioning and could make complete revolutions.

Figure 4.10: Fully functioning pivot irrigating in June 2021.

Figure 4.11 shows the Rehabilitated Field in June 2022.

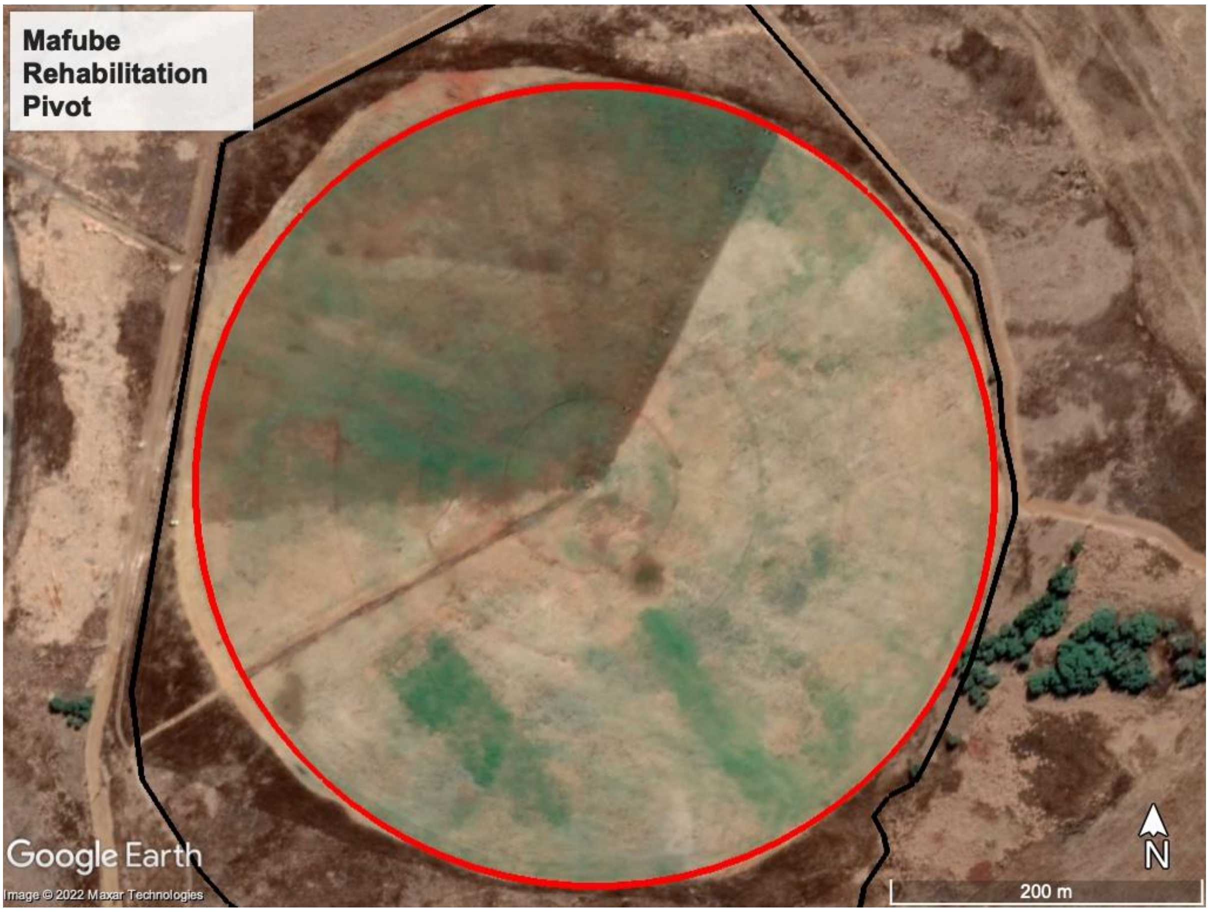


Figure 4.11: Google Earth image from the Rehabilitation Field, June 2022.

Knowing the history and progression of the rehabilitation process is important for understanding the variability of the area and determining the initial soil properties. The next chapter will evaluate the state of the rehabilitated area and how to get rehabilitated land to an irrigable standard.

4.2 Establishing irrigation in a mining environment

Setting up an irrigation program in or next to an active mining environment can be a difficult process with many unexpected challenges. This section briefly discusses the challenges and difficulties faced during the irrigation setup on rehabilitated land. This information may be helpful for future projects of setting up irrigation in a mining environment.

It is important to keep in mind when working in a mining environment that coal production and any processes related to this are prioritized by the mine. This relates to staff support, water supply, and machinery to assist with earthworks. Communication also needs to follow a chain of command for obtaining approvals or any authorizations for work to be conducted. This includes work that is done off-site, but by staff members of the mine.

Proper planning can eliminate most of the difficulties when it comes to soil preparation and pivot set-up or maintenance as extra time for delays can be incorporated into the timeframe. The main challenge occurs when a crop is planted and irrigation is necessary. This is the crucial time where a small delay in water availability or power supply can affect the success of the crop. A pump that is designated for irrigation only is necessary. This will eliminate any competition for water between mining and rehabilitation.

Securing equipment against theft is crucial as this can result in the downfall of a cropping season. Although it is relatively easy to replace stolen equipment or cables it is expensive and can take a few days.

4.3 Conclusion

Although only limited information was available regarding the historical data for the Rehabilitation Field at Mafube, satellite images from Google Earth did present some information regarding the timeframe and rehabilitation processes. A clear difference in soil colour was visible which is indicative of the variability in soil conditions.

Setting up an irrigation project in a mining environment requires sufficient planning. Proper irrigation scheduling is required to compensate for any unexpected challenges that can cause delays in irrigation. Good collaboration between the mine and the irrigation team is crucial and can determine the success of the project.

From this chapter, it is clear that high variability in soil conditions will be present in the Rehabilitation Field. In the next chapter, the extent of the variability in soil physical and chemical properties are presented, as well as indications as to how such variability affects crop growth.

Chapter 5: Weed growth in relation to soil physical and chemical properties

5.1 Introduction

Before it was possible to grow crops commercially at the Rehabilitated Pivot, weed growth was considerable over the whole area in the summer, with variability in growth clearly visible. Major variations in bulk density, root growth, compaction and soil chemistry were expected across the pivot area due to the variety of soil types brought in during the rehabilitation process (Chapter 4), and the severe compaction generated by the heavy equipment used to bring in the soil. It was therefore decided to evaluate in detail, the effects of variations in soil chemical and physical characteristics on weed growth, as a surrogate for effects on crop growth that could only be measurable after successful cropping of this field.

This Chapter provides data on the variability of soil physical and chemical parameters across the rehabilitated field, and relates this variability in soil conditions to plant growth.

5.2 Sampling point location, methodology and results

Sampling location

Soil sampling and measurements were done before any soil preparation started at the Rehabilitated Field. Soil physical conditions, chemical constituents and yield of weeds were measured and analysed.

Thirty-two sampling locations were selected over the Rehabilitated Field. At each location the following readings or samples were taken:

- 4 soil samples were taken from 0-300 mm depth; one from the centre of each of three 0.75 m x 0.75 m plant sampling squares, and a fourth sample from the centre of the sampling point (see detail in Figure 5.2). These samples were mixed to generate 1 sample per site
- Soil samples 300-600mm and 600-900mm depth, one from the centre of each sampling point
- Three penetrometer measurements in each square, nine in total at each sample location
- Weed dry matter yield (0.75m x 0.75m) 3 samples per location
- Clod samples (for bulk density)

Figure 5.1 indicates the sampling points at the Rehabilitated Field and Figure 5.2 illustrates where plant and soil samples, and penetrometer readings were taken within each sampling point location. Details of the sampling methods, sample preparation and analyses undertaken, follow.

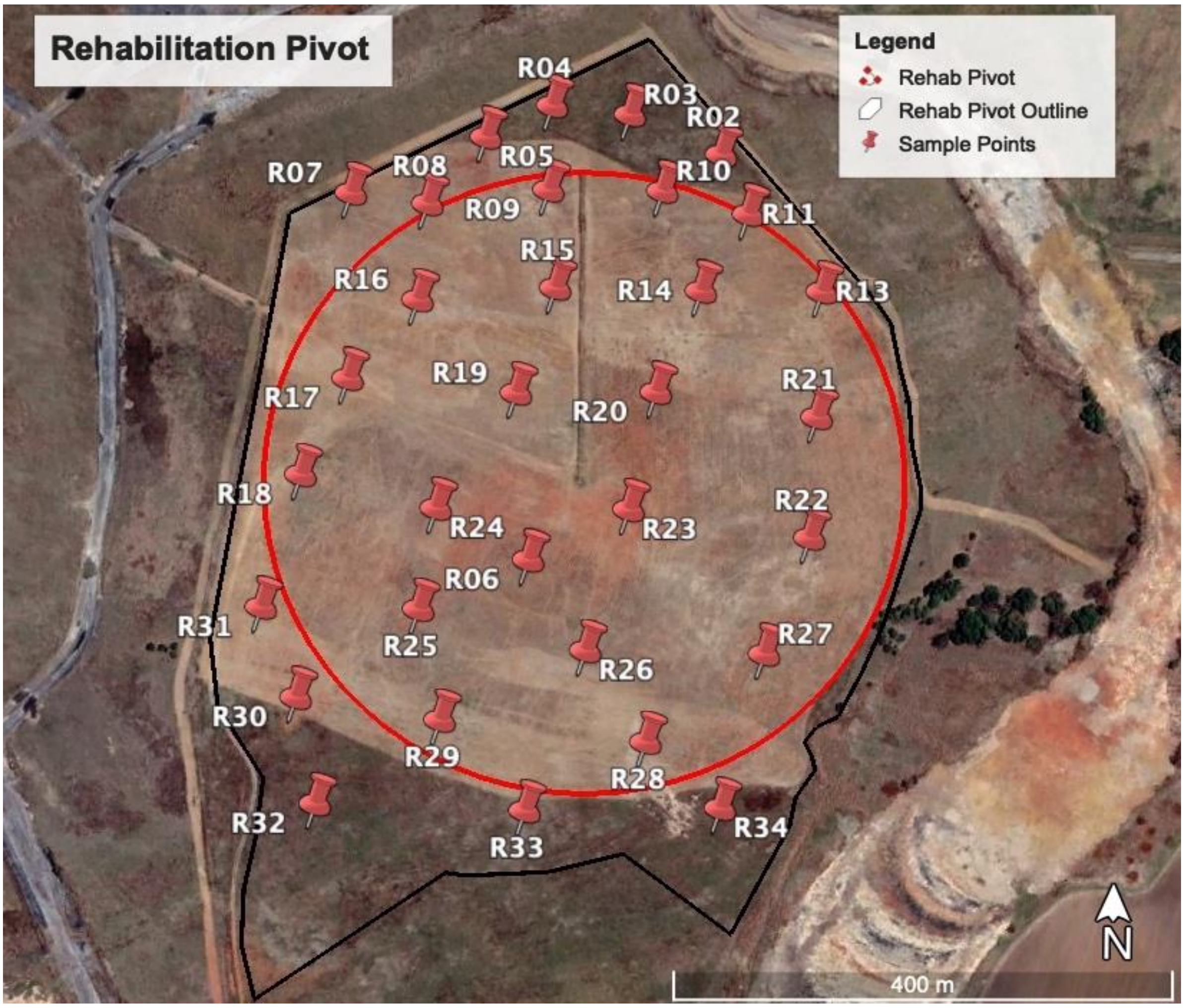


Figure 5.1: Sampling points at the Rehabilitatied Field.

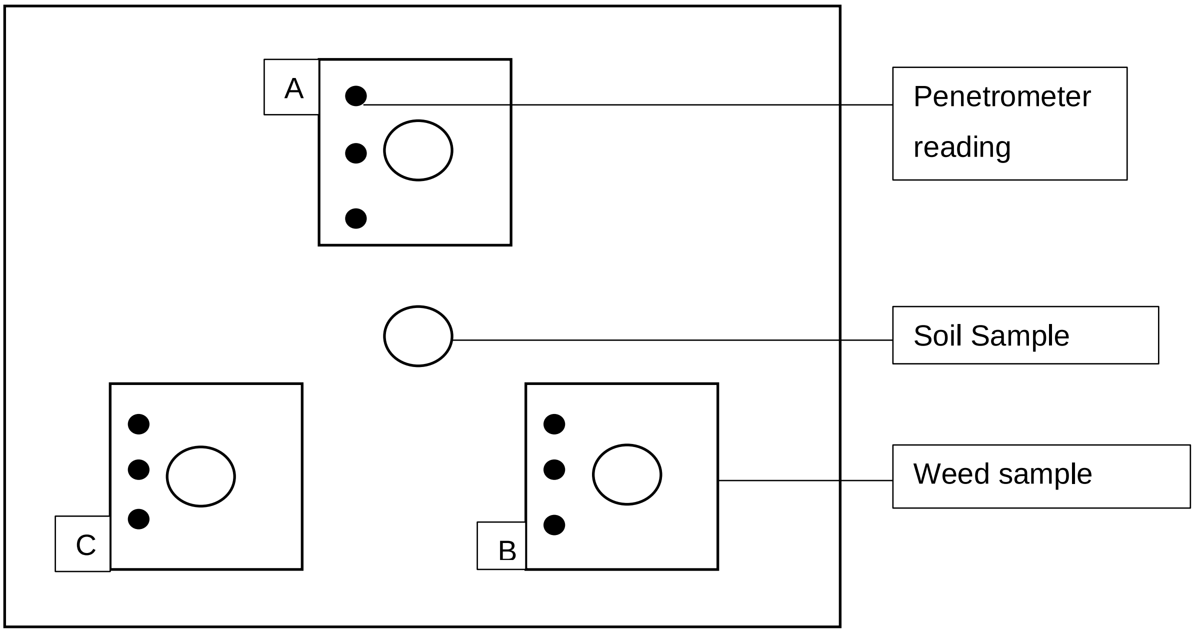


Figure 5.2: Typical distribution of monitoring points within a sampling location at the Rehabilitation Field.

Penetrometer measurements and soil samples were randomly taken from the unmined field adjacent to the Rehabilitated Field. This was done to determine the difference in variability between unmined and rehabilitated land.

Sampling Methodology

The rehabilitated area was covered in weeds, which provided a useful initial measure of suitability of the land for plant growth. Due to the failure to establish crops, it was decided to use weed growth to provide an indication of the relationship between soil chemical and physical characteristics of rehabilitated land, and plant growth, although it is appreciated that it could not be assumed that weed seed density and species composition was uniform over the whole field.

A total of 96 weed samples, three from each of 32 sample locations, were taken over the rehabilitated field, both inside and outside the irrigation area. This was to have 3 replicates for each sample point. Within each sample location, three steel squares (0.75 m x 0.75 m), were placed around the sample point. Square A, was located 1 m to the north, square B, 1 m southeast and square C, 1 m southwest of the centre point. This was done to eliminate the human factor and to maintain sample integrity. All plant material inside the square was cut off directly above the ground and collected. The dry mass harvested in the 0.75 m x 0.75 m squares were converted to $1m^1$ afterwards. This was done to decrease the amount of material collected to ease the process of transport and handling as high yields were present.

Figure 5.3 demonstrates plant material sampling. The composition of the weeds collected was mainly Cosmos (*Cosmos bipinnatus)*, and occasionally Johnson grass, (*Sorghum halepense)*.

Samples were taken in April 2021 when most of the weeds were fully grown and mature. Samples were initially dried at 65 ºC for 24 to 27 hours. From 27 hours, weeds were weighed every 4 hours and returned to the oven until a constant mass was obtained. The weights of the samples were converted from g/m^2 to t/ha.

Figure 5.3: Steel square (0.75 m x 0.75 m) within which all plant material was sampled.

Soil samples were taken for chemical analysis of the rehabilitated area. As shown in Figure 5.2, four soil samples were taken at each sample point at a depth of 0-300 mm. The four samples were mixed and one composite sample was taken to represent the sampling location. High variability over the rehabilitated field was expected.

Because these were the first soil samples taken post-rehabilitation and before the commencement of irrigation, these samples provide a baseline from which changes over time due to mine water irrigation can be detected. Analyses included pH (H_2O), organic carbon (Walkley Black), and macro nutrients and micro nutrients using a Mehlich-3 extract.

The short-term objective of this section was to determine if weed growth could be related to soil fertility or physical properties. Figure 5.4 shows soil sampling, which was done directly after the weeds had been sampled. Sample R34 was contaminated during lab trials and discarded.

Figure 5.4: Soil sampling in the Rehabilitated Field.

The Dynamic Cone Penetrometer (DCP) is frequently used to provide a quick and simple indication of soil compaction (De Moraes et al., 2014). The DCP was designed in South Africa by Kleyen and its original purpose was for pavement applications as an indicator of soil resistance (Mogotsi & Van der Merwe, 2017).

The Dynamic Cone Penetrometer, shown in Figure 5.5, consists of two shafts (16 mm diameter) coupled near the midpoint. The lower shaft contains a pointed tip which is driven into the soil. The 8 kg free-falling sliding hammer on the upper shaft is lifted to the top and allowed to fall 575 mm onto the anvil between the shafts, which drives the pointed tip into the soil. After each blow, the distance the shaft penetrates the soil is measured. These distances are used to determine soil strength.

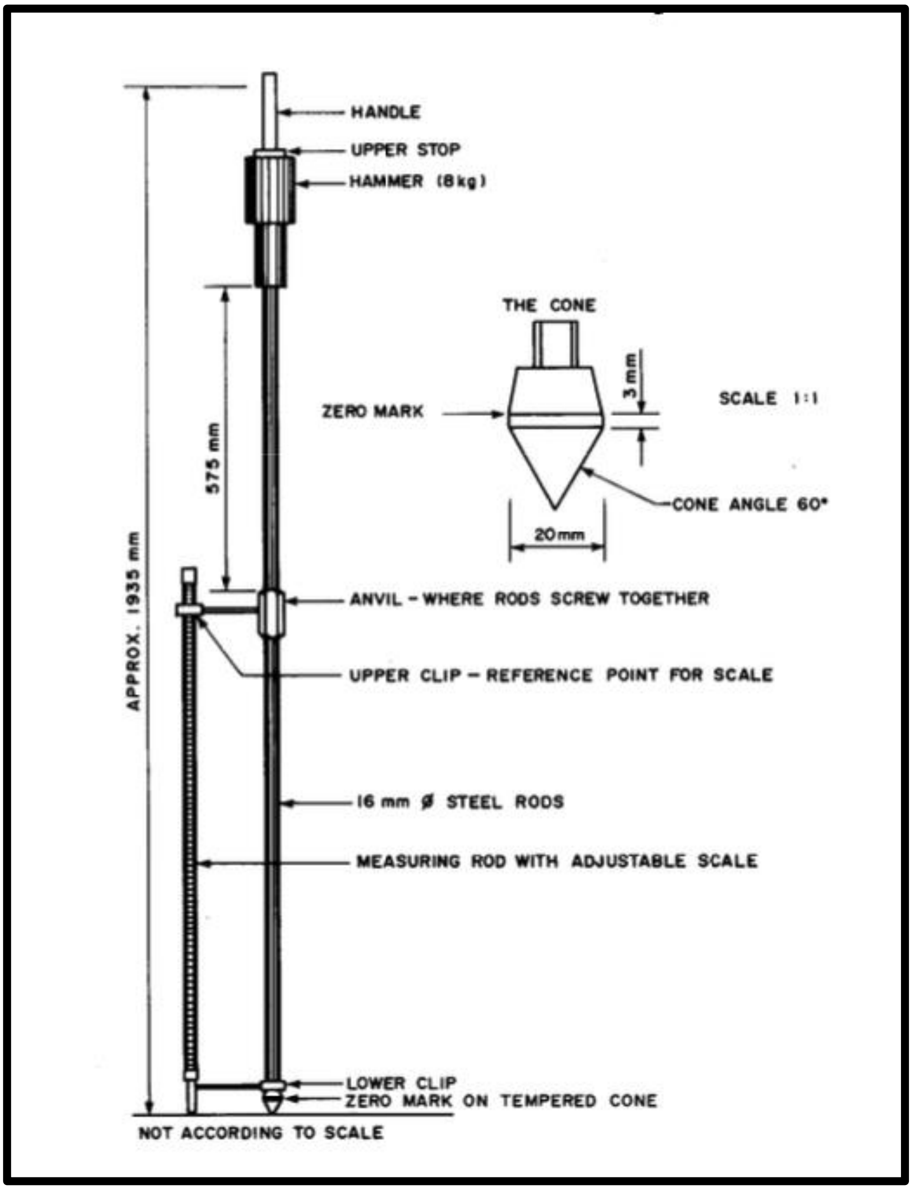


Figure 5.5: The Dynamic Cone Penetrometer (Paige-Green & Du Plessis. 2009).

Within each sample location, nine penetrometer measurements were made, three within each square (as seen in Figure 5.2). Two of the sampling points, R28 and R30, were inaccessible during penetrometer sampling due to high snake activity in those specific areas. Sample locations R3 and R4 were not measured due to the penetrometer breaking and soil preparation commencing for the winter crop.

Figure 5.6 shows a staff member assisting with the penetrometer readings at the Rehabilitated Field.

Figure 5.6: Penetrometer measurements in the field.

Soil penetrometer measurements were done in May when the soil was uniformly dry, and before any soil preparation for the winter crop. A greater number of blows per 100 mm indicates higher resistance to penetration within the soil. With some measurements, penetration was deemed to have reached the point of refusal when penetration was less than 1cm after per 8 blows. This refusal to penetrate was not due to rock presence in the horizon, as the reaction of the penetrometer to rock was different and easily discernible. When rock was encountered, a separate measurement was made a few centimetres away from the original point.

Bulk density measurements are routinely used to investigate different soil properties, but most commonly to measure soil compaction. There are different methods for measuring soil bulk density. The clod method was used in this study due to limited time for sampling before soil preparation commenced. Soil was overturned with a normal garden fork at a depth of 0-250 mm. Clods were collected from the overturned soil at each sampling location and the wax method was used (Le Roux et al., 2019). Original clod sizes were around 500 g, but were split into smaller clods for ease of analysis. This is the reason for the small clod sizes typically used in the wax method.

The volume is determined by coating a clod of known dry (oven dried at 65 ºC for three days) mass with a water-repellent substance (wax) and by weighing it first in air, then again while immersed in a liquid of known density, in this case, water. Bulk density can be calculated by dividing the mass of the clod with the volume of the clod.

5.3 Results and discussion

Table 5.1 presents the plant biomass of each individual 0.75 x 0.75 m sample, and the average mass of all three samples for each sampling location.

There was great variability in the average mass between sample locations, and also high variability between the three samples within each location. Samples in Table 5.1 are sorted from highest to lowest average t/ha.

Table 5.1: Weed mass of samples collected at the Rehabilitated Field in April 2021

Sample location	A	B	C	Average
	t/ha	t/ha	t/ha	t/ha
R20	6.5	8.3	7.3	7.4
R08	9.0	5.7	6.0	6.9
R22	6.1	5.6	8.1	6.6
R07	9.5	4.5	3.9	6.0
R16	4.0	7.8	4.8	5.5
R25	4.8	5.0	6.7	5.5
R11	8.3	4.1	3.9	5.5
R04	5.5	5.5	5.3	5.4
R05	6.0	6.4	3.6	5.3
R10	4.0	7.9	4.2	5.3
R19	4.9	4.2	6.2	5.1
R21	6.7	4.7	3.8	5.1
R06	4.3	4.6	5.9	4.9
R33	4.6	4.4	5.1	4.7
R03	5.8	5.1	3.2	4.7
R14	3.1	4.9	5.6	4.5
R30	5.3	4.6	3.6	4.5
R13	5.2	4.9	3.2	4.4
R09	3.0	4.0	6.1	4.4
R29	6.1	3.9	2.9	4.3
R27	3.7	4.3	4.7	4.2
R02	6.2	3.0	3.4	4.2
R28	4.0	4.5	3.4	3.9
R15	3.2	4.7	2.2	3.3
R32	3.5	3.3	3.2	3.3
R31	3.8	1.7	4.4	3.3
R23	4.9	1.7	3.1	3.2
R34	2.4	3.1	2.9	2.8
R26	3.5	1.9	2.7	2.7
R24	3.8	2.1	1.6	2.5
R18	2.3	1.3	1.2	1.6
R17	1.3	1.3	1.4	1.3

Table 5.2 presents a summary table of chemical analyses together with the average total above ground dry matter of weeds (TDM) in t/ha. The table is sorted according to yield from highest to lowest.

Table 5.2: Summarized chemical analysis of the Rehabilitated Field, together with above ground dry matter yields of weeds at several sampling locations

Sample	pH (H_2O)	%C	P	K	Ca	SO4	Fe	TDM
			mg/kg	mg/kg	Mg/kg	mg/kg	mg/kg	t/ha
R20	6.1	0.5	10	101	369	28	37	7.4
R08	5.8	0.5	11	55	188	19	90	6.9
R22	6.1	0.5	5	55	519	34	71	6.6
R07	6.7	1.2	53	129	1218	22	78	6.0
R25	6.4	0.6	16	62	616	22	57	5.5
R11	6.4	0.6	6	96	579	24	55	5.5
R04	5.5	0.5	15	65	331	35	99	5.4
R05	6.2	0.5	6	96	576	32	51	5.3
R10	6.9	0.7	9	103	870	21	63	5.3
R19	6.4	0.7	7	147	819	23	78	5.1
R21	6.0	0.5	7	64	468	32	84	5.1
R06	6.4	0.4	5	38	497	22	41	4.9
R16	5.6	0.4	6	34	290	66	49	4.8
R03	6.4	0.5	5	77	579	30	59	4.7
R14	6.3	0.5	4	76	515	25	61	4.5
R30	5.5	0.5	15	65	331	35	99	4.5
R13	6.1	0.4	11	70	384	28	59	4.4
R09	7.1	0.6	4	128	745	21	94	4.4
R29	6.3	0.6	12	90	552	21	48	4.3
R27	6.4	0.5	5	77	579	30	59	4.2
R02	6.3	0.5	7	95	464	20	52	4.2
R28	6.4	0.6	7	78	631	24	68	3.9
R15	6.3	0.7	5	100	570	28	66	3.3
R31	6.1	0.4	3	32	396	35	93	3.3
R23	5.4	0.5	12	31	311	90	35	3.2
R26	6.5	0.6	14	152	849	26	63	2.7
R24	6.2	0.5	6	83	457	36	72	2.5
R18	6.6	0.5	2	47	481	49	58	1.6
R17	6.0	0.4	8	51	411	53	42	1.3
Average	6.2	0.5	9	79	538	32	65	4.6

Variability across the rehabilitated field, shown in Table 5.2, is high. For rehabilitated soil, the high variability is expected but is uncommon for arable agricultural soil. This may also be the result of different soil types being trucked in during the rehabilitation process. Table 5.3 presents chemical analyses of soils from a pivot on unmined land adjacent to Mafube. Variability of these samples is much lower than that for the rehabilitated land.

Table 5.3: Summarized chemical analysis of the unmined irrigable land adjacent to the Rehabilitated Field

Sample	pH	% C	P	K	Ca
			mg/kg	mg/kg	mg/kg
S01	5.5	0.9	105	96	529
S03	6.4	0.9	86	186	772
S13	6.2	1.0	74	88	775
S08	6.6	0.9	97	212	722
S11	5.9	1.1	63	138	735
S04	6.5	0.9	82	160	805
S02	5.6	0.9	104	90	523
S17	6.1	0.8	83	93	764
S20	6.6	1.3	48	248	1288
S21	6.1	1.0	71	130	870
S18	5.9	1.3	59	171	1061
S15	6.4	1.0	73	103	564
Average	6.1	1	79	143	784

The overall fertility of the Rehabilitated Field was also much lower than that of the unmined and regularly cropped pivot. While pH of the rehabilitated land differs little from that of the unmined land, there are large differences in respect to organic carbon, P, K and Ca. Comparing the averages of some fertility indicators from Tables 5.2 and 5.3, in Figure 5.7, shows there are clear differences between undisturbed (unmined) and rehabilitated mine land.

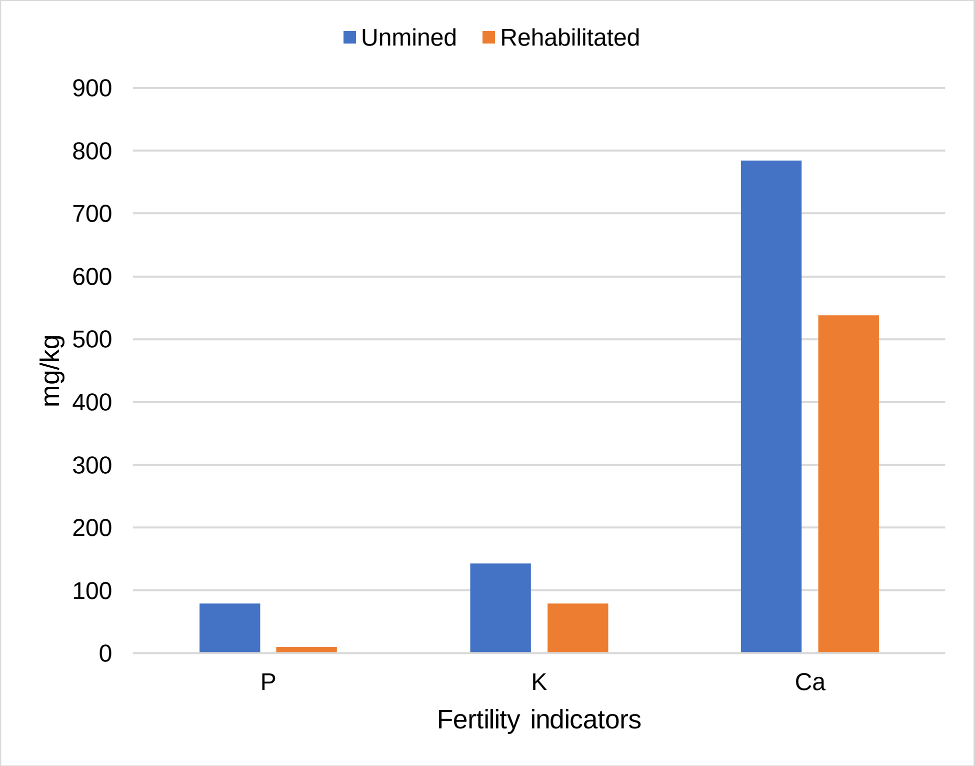


Figure 5.7: Fertility compared between unmined and rehabilitated land

Penetrometer readings are summarized in Table 5.4 and presented as the number of blows required to reach certain depths.

Table 5.4: Penetrometer readings (number of blows to specific depths) in relation to weed yield

Sample	Yield (t/ha)	Number of blows 0-100 mm	Number of blows 100-200 mm	Number of blows 200-300 mm	Number of blows 300-400 mm
R 20	7.4	1	7	11	18
R 08	6.9	1	4	8	6
R 22	6.6	3	7	13	20
R 07	6	1	5	11	14
R 11	5.5	1	2	6	10
R 16	5.5	1	1	6	10
R 25	5.5	1	3	*	***
R 05	5.3	1	3	5	4
R 10	5.3	2	5	13	***
R 19	5.1	1	3	14	32
R 21	5.1	1	2	5	8
R 06	4.9	1	6	8	6
R 33	4.7	2	*	*	***
R 14	4.5	1	5	9	11
R 30	4.5	-	-	-	-
R 09	4.4	3	8	9	10
R 13	4.4	3	8	10	12
R 29	4.3	1	5	8	7
R 02	4.2	3	4	6	6
R 27	4.2	1	3	12	16
R 28	3.9	-	-	-	-
R 15	3.3	1	5	11	*
R 31	3.3	2	*	*	***
R 32	3.3	1	3	9	7
R 23	3.2	2	6	*	**
R 34	2.8	2	4	7	18
R 26	2.7	1	3	6	16
R 24	2.5	2	*	*	*
R 18	1.6	**	**	**	**
R 17	1.3	2	**	**	***

*One penetrometer measurement reached refusal at this depth
** Two penetrometer measurements reached refusal at this depth
*** Three penetrometer measurements reached refusal at this depth.

Table 5.5 represents sampling locations with clear restricting layers present and the depth of the layer. Six sample locations with no layer present are also included in the table as the data in Table 5.5 is used in Chapter 7 to predict the irrigable potential for different sampling sites in the rehabilitated area.

Table 5.5: Sampling sites showing clear indications of restricting layers (depth) and sites showing no indications of restricting layers present

Sample Site	Clear restricting layer present	Depth (cm)
R 02	No	-
R 05	No	-
R 06	No	-
R 09	No	-
R 18	No	-
R 29	No	-
R 20	Yes	30
R 13	Yes	30
R 19	Yes	30
R 27	Yes	25
R 16	Yes	60
R 25	Yes	30
R 15	Yes	20
R 17	Yes	15

Table 5.6 presents the bulk density obtained from the wax clod method. Some of the samples were too poorly structured for the wax method to work. These clods simply fell apart when handled. This was the case for samples R3, R4, R10 and R32.

Table 5.6: Bulk density at the measured locations sorted from highest to lowest yield

R Sample	Clod (g)	Clod Volume (cm3)	Density (g/cm3)	Yield (t/ha)
20	21.3	10.6	2.0	7.4
8	12.6	6.4	2.0	6.9
22	18.5	9.5	1.9	6.6
7	11.2	5.5	2.0	6
11	20.6	10.1	2.0	5.5
21	15.8	7.8	2.0	5.5
5	8.5	4.3	2.0	5.3
19	12.8	5.6	2.3	5.1
6	26.2	12.9	2.0	4.9
16	32.6	17.4	1.9	4.8
14	13.9	7	2.0	4.5
9	15.7	7.3	2.2	4.4
29	40.8	23.4	1.7	4.3
27	25.1	12.7	2.0	4.2
28	18.3	9.2	2.0	3.9
15	26.6	13	2.0	3.3
31	14.7	6.7	2.2	3.3
23	11.1	6.7	1.7	3.2
26	18.8	10.6	1.8	2.7
24	17	8	2.1	2.5
18	14.2	6.7	2.1	1.6
17	21.5	10	2.2	1.3

High variability was expected over the area but was not observed, with all samples exhibiting high levels of compaction. The high density indicates overall compaction over the Rehabilitated Field. It can be assumed that ripping, while opening up pathways to greater depth for rooting, may not disturb the integrity of the clods themselves. It was therefore decided to use only the penetrometer measurements to identify compaction in the rehabilitated field.

Variability between the unmined and Rehabilitated Field

The soil analysis showed high variability in the chemical properties of the Rehabilitated Field compared to the unmined field. Penetrometer readings presented in graphs assist in identifying and visualising soil resistance through the profile. Small and abrupt changes over a short distance indicate a restricting layer in the profile. High variability in physical properties were expected in the Rehabilitated Field. Figure 5.8 represents penetrometer readings from five random sites in the rehabilitated field and Figure 5.9 from the unmined field.

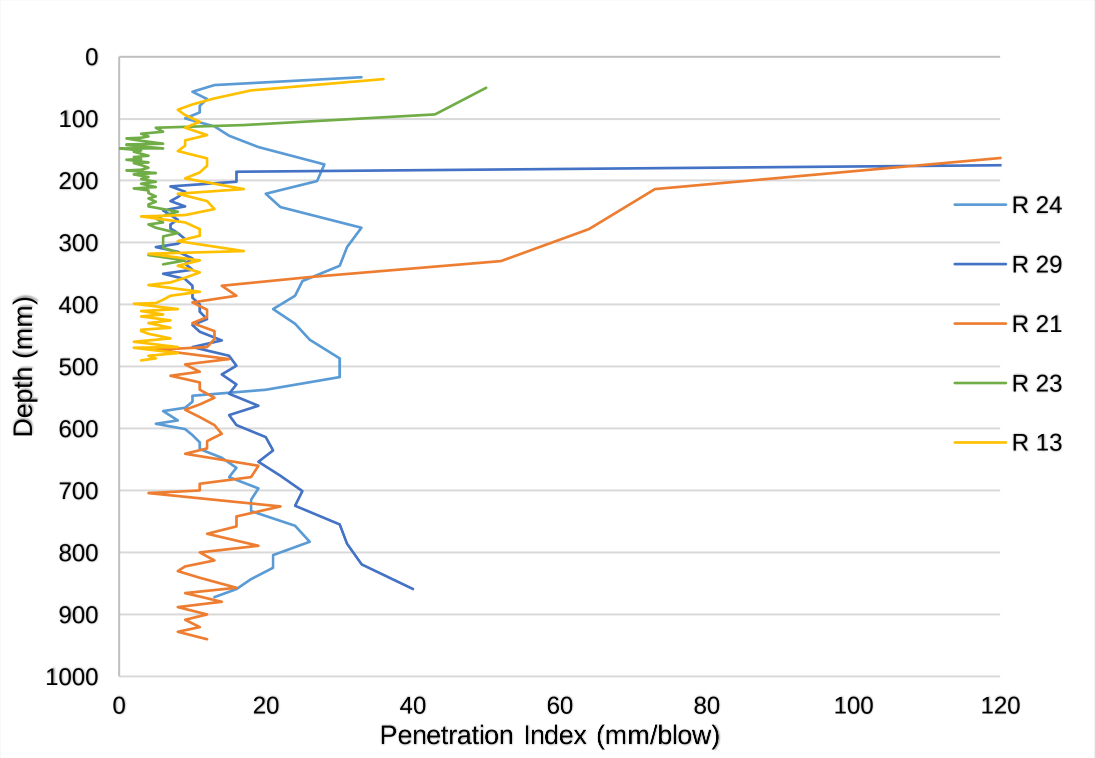


Figure 5.8: Five random penetrometer readings from the Rehabilitated Field.

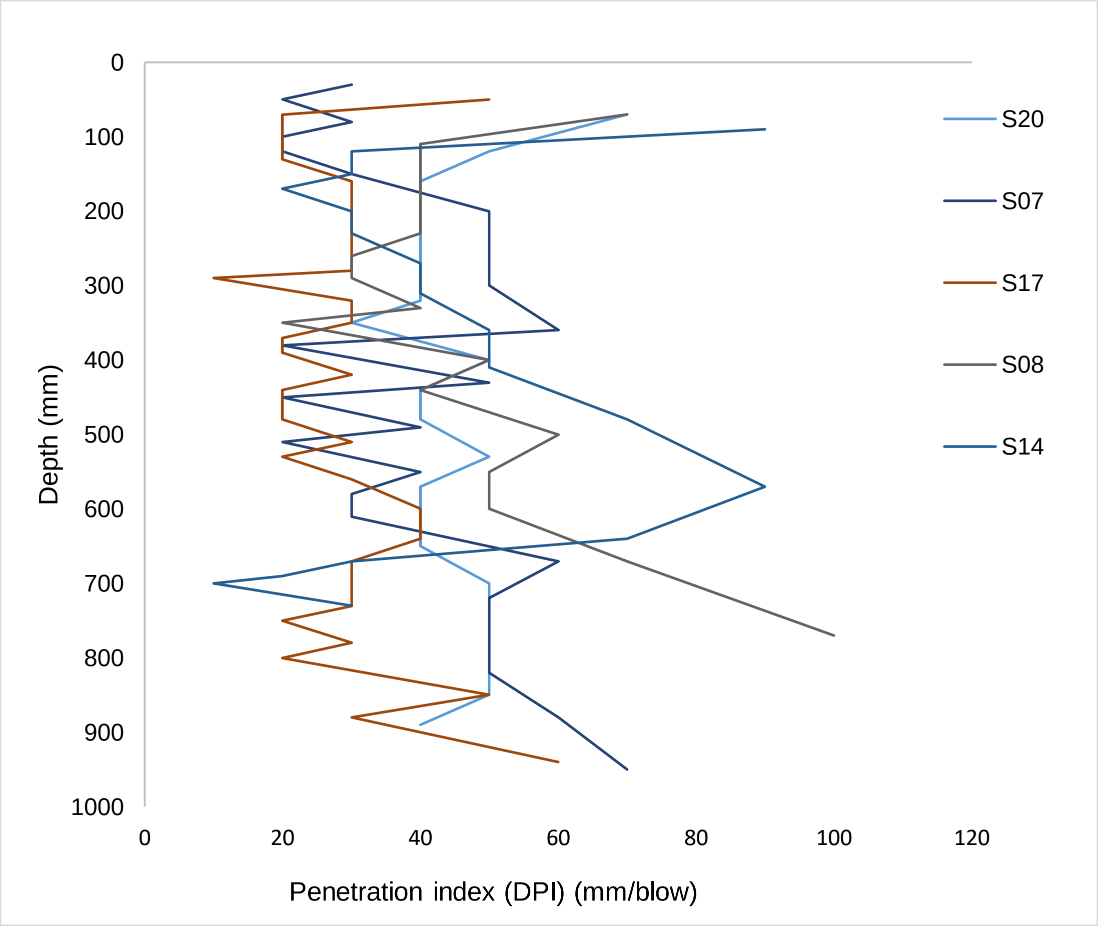


Figure 5.9: Five random penetrometer reading from the unmined field.

The graphs presented in Figure 5.8 and 5.9 shows a clear difference in physical properties between rehabilitated land and unmined land. The rehabilitated land exhibits greater variability than the unmined land. Compaction is much higher in the rehabilitated than the unmined land. The goal would be to reduce overall compaction. To achieve this, proper ripping at a depth of at least 1m is required.

Weed growth compared to chemical properties

The physical and chemical properties of the sample locations in the Rehabilitated Field were compared with weed growth to determine to what extent the variability of soil physical and chemical parameters affected plant yield. This initial evaluation relates soil characteristics to weed growth by comparing low and high values for each constituent or measurement, with weed growth.

Multiple chemical properties were compared to weed growth to identify any relation between it and chemical properties of the soil.

Table 5.7 shows yield in relation to pH above 6.5 and below 6. Five of the samples have a pH above 6.5 and five are below pH 6. There is no indication that yield is related to soil pH. Potassium concentration decreased with decreasing pH, but phosphorus does not seem to be related to pH.

Table 5.7: Yield of weeds for samples with soil pH above 6.5 and below 6

Sample	**pH**	**TDM**	**P**	**K**
		t/ha	**mg/kg**	**mg/kg**
pH above 6.5				
R09	7.1	4.4	4	128
R10	6.9	5.3	9	103
R07	6.7	6.0	53	129
R18	6.6	1.6	2	47
R26	6.5	2.7	14	152
Average	6.8	4.0	16	112
pH below 6				
R 08	5.8	6.9	11	55
R16	5.6	4.8	6	34
R 04	5.5	5.4	15	65
R 30	5.5	4.5	15	65
R23	5.4	3.2	12	31
Average	5.6	5.0	12	50

Data from Table 5.7 indicates that weed yield did not decrease with soil pH values below 6. Chemical analysis shows very low P and K concentrations at R18, and one of these factors may be responsible for the low yield in this case.

Table 5.8 represents yield in relation to the percentage of carbon at or above 0.7% and at or below 0.4%. Yields are higher with organic carbon at or above 0.7% than with organic carbon at below 0.4%. There is a correlation between organic carbon and potassium but no apparent correlation between phosphorus and organic carbon.

Table 5.8: Yield of weeds for samples with soil %C at or above 0.7 and at or below0.4

	%C	**TDM**	**pH**	**P**	**K**
		t/ha		**mg/kg**	**mg/kg**
%C at or above 0.7					
R07	1.2	6.0	6.7	53	129
R19	0.7	5.1	6.4	7	147
R15	0.7	4.2	6.3	5	100
R10	0.7	5.3	6.9	9	103
Average	0.8	5.2	6.6	18	120
%C at or below 0.4					
R13	0.4	4.4	6.1	11	70
R06	0.4	4.9	6.4	5	38
R31	0.4	3.3	6.1	3	32
R16	0.4	5.5	5.6	6	34
R17	0.4	1.3	6.0	8	51
Average	0.4	3.9	6.0	7	45

Organic matter in soil is extremely difficult to increase sustainably, and a “quick fix” is not possible. Once topsoil, which has high carbon content, is mixed with spoil or other subsurface layers of soil which contain very little carbon, organic carbon will be diluted. Research in temperate climates indicates that it may take up to 100 years to reinstate the organic carbon status of topsoil once it is lost.

Yield is related to both phosphorus and potassium. Both these values would be recognised as being extremely low in cropping soils.

The higher values of both constituents are related to higher weed growth. Table 5.9 shows yield related to phosphorus levels of 15 mg/kg and more, versus 4 mg/kg and less.

Table 5.9: Yields for samples with a phosphate concentration at or above 15 mg/kg and at or below 4 mg/kg

Sample	**P**	**TDM**	**K**	**pH**
	mg/kg	**t/ha**	**mg/kg**	
At or above 15 mg/kg				
R07	53	6.0	129	6.7
R25	16	5.5	62	6.4
R 04	15	5.4	65	5.5
R 30	15	4.5	65	5.5
Average	27	5.4	80	6.0
At or below 4 mg/kg				
R09	4	4.4	128	7.1
R 14	4	4.5	76	6.3
R31	3	3.3	32	6.1
R18	2	1.6	47	6.6
Average	3.3	3.5	71	6.5

Phosphorus concentrations over the Rehabilitated Field, which averaged 9 mg/kg, are generally much lower than what would be recommended for good arable cropping. Values at or below 4 mg/kg are particularly low and accordingly, it is no surprise that yields with this level of soil P are significantly lower than yields with P of 15 mg/kg and above.

Table 5.10 compares yields from soils with potassium levels below 40 mg/kg with soils with potassium levels in excess of 120 mg/kg.

Table 5.10: Yields for samples with a potassium concentration of 120 mg/kg and more and less than 40 mg/kg

Sample	**K**	**TDM**	**P**	**pH**
	mg/kg	**t/ha**	**mg/kg**	
120 mg/kg and more				
R26	152	2.7	14	6.5
R19	147	5.1	7	6.4
R07	129	6.0	53	6.7
R09	128	4.4	4	7.1
Average	139	4.6	19	6.7
Less than 40 mg/kg				
R06	38	4.9	5	6.4
R16	34	5.5	6	5.6
R31	32	3.3	3	6.1
R23	31	3.2	12	5.4
Average	34	4.2	6.5	5.9

Table 5.10 indicates that there is little correlation between soil potassium levels and weed yield, despite the concentration of potassium (less than 40 mg/kg) being well below levels at which crop response would be expected. Potassium levels at the rehabilitated field are lower than the average concentration in an arable field in the same area (as shown in table 5.5).

There is some significant variability in yield that does not seem to be related to soil chemistry, and this may be related to the soil's physical characteristics. For instance, Sample R17 has higher fertility than samples R06, R16 and R31, but a much lower yield. This may be the result of physical conditions affecting yield. Weed growth and physical properties of the soil are now compared and discussed to determine if weed growth is more related to physical properties than chemical properties.

Weed growth compared to physical properties

It is clear from Table 5.2 that all high yielding (more than 6 t ha^{-1}) locations showed no penetrometer refusals in the top 400 mm of soil, while the lowest yielding locations all showed penetrometer refusal in the upper soil horizons. Graphs from high yield to low yield areas are presented to determine whether the growth can be related to physical conditions. These graphs assisted with determining the depth at which a restricted layer is present, if any. All of the graphs are included in Appendix B.

Compaction normally restricts root growth and the downward movement of water and nutrients. Figure 5.10 represents the penetrometer readings of the four locations with the lowest yield and Figure 5.11 the four locations with the highest yields.

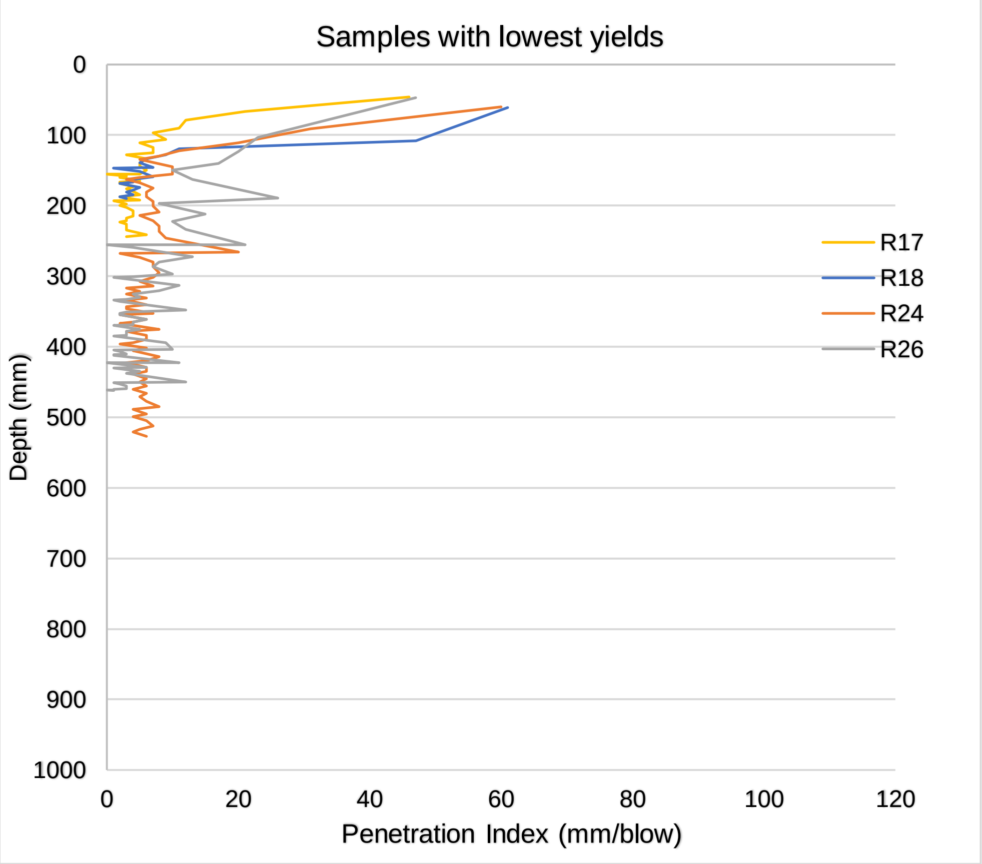


Figure 5.10: Average penetrometer readings of the four samples with the lowest yield.

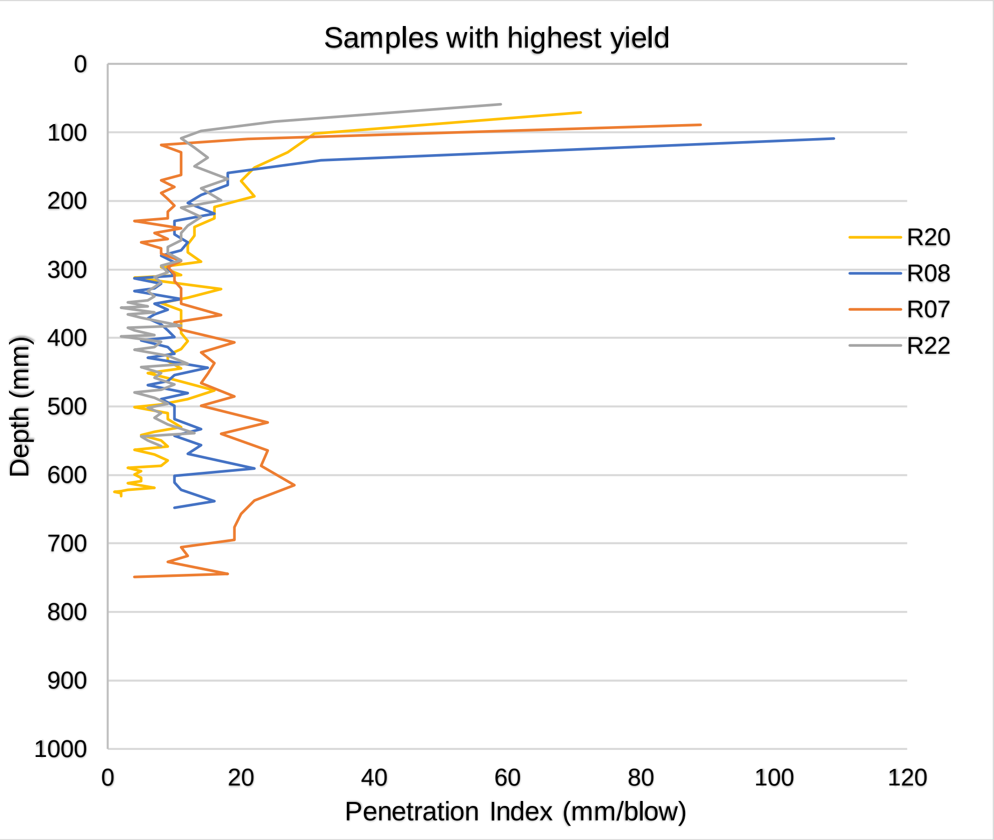


Figure 5.11: Average penetrometer readings of the four samples with the highest yields.

Figures 5.10 and 5.11 indicate that yield difference is related to soil resistance to penetration. Figure 5.10 indicates that a restricting layer is reached in every case before 300 mm, with some of the restricting layers starting as shallow as 100 mm. High yield samples (Figure 5.11) show some increase in resistance, but there are no fully restricting layers till a depth of 700 mm. The soil resistance to penetration is much lower in the 200-600 mm depth interval in the higher yielding plots than in the low yielding plots. The four high yield locations are distributed widely over the field and in a variety of soil types.

It was demonstrated earlier, where the relationship between soil chemical constituents and yield was examined, that there were several low yielding areas that could not be explained by soil chemistry. For example, location R26 had high P and K concentrations compared to other samples, but lower yields. Figure 5.12 represents three average penetrometer samples from R26. Small and abrupt changes over a short depth indicate a boundary layer or compaction (over a longer depth) in the soil. The top 22 cm indicates normal soil with good penetration potential but from 22 cm and deeper, there is a clear boundary layer visible that represents compaction.

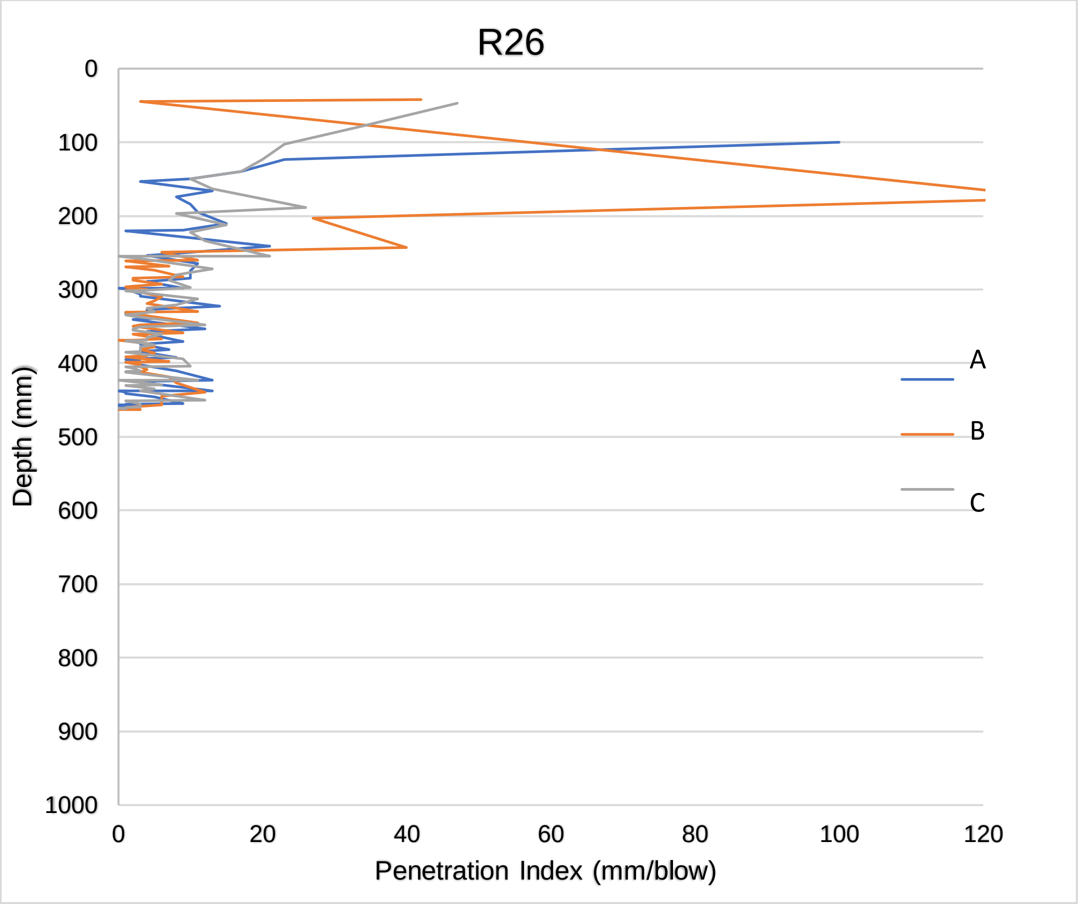


Figure 5.12: Penetrometer measurements at R26 indicating compaction.

It is, therefore, probable that the lower yield of R26 is due to physical conditions and not fertility. The restricting layer in Figure 5.12 will minimise downward movement of water or roots. Figure 5.1, at the start of this chapter, shows the location of the sampling points in the Rehabilitated Field. It was clear that at R26, soil had been trucked in and levelled afterwards. This compaction was most likely due to the heavy machinery used, compacting loose soil, which had not subsequently been loosened by ripping.

Figure 5.13 illustrates two average penetrometer results from R16 and two from R17 compared to each other. R16 had a yield of 5.5 t/ha and R17 had a yield of 1.3 t/ha. R17 shows a restricting layer that starts from 10 cm and R16 only shows a layer below 60cm. The lower yield of R17 may therefore be a result of compaction.

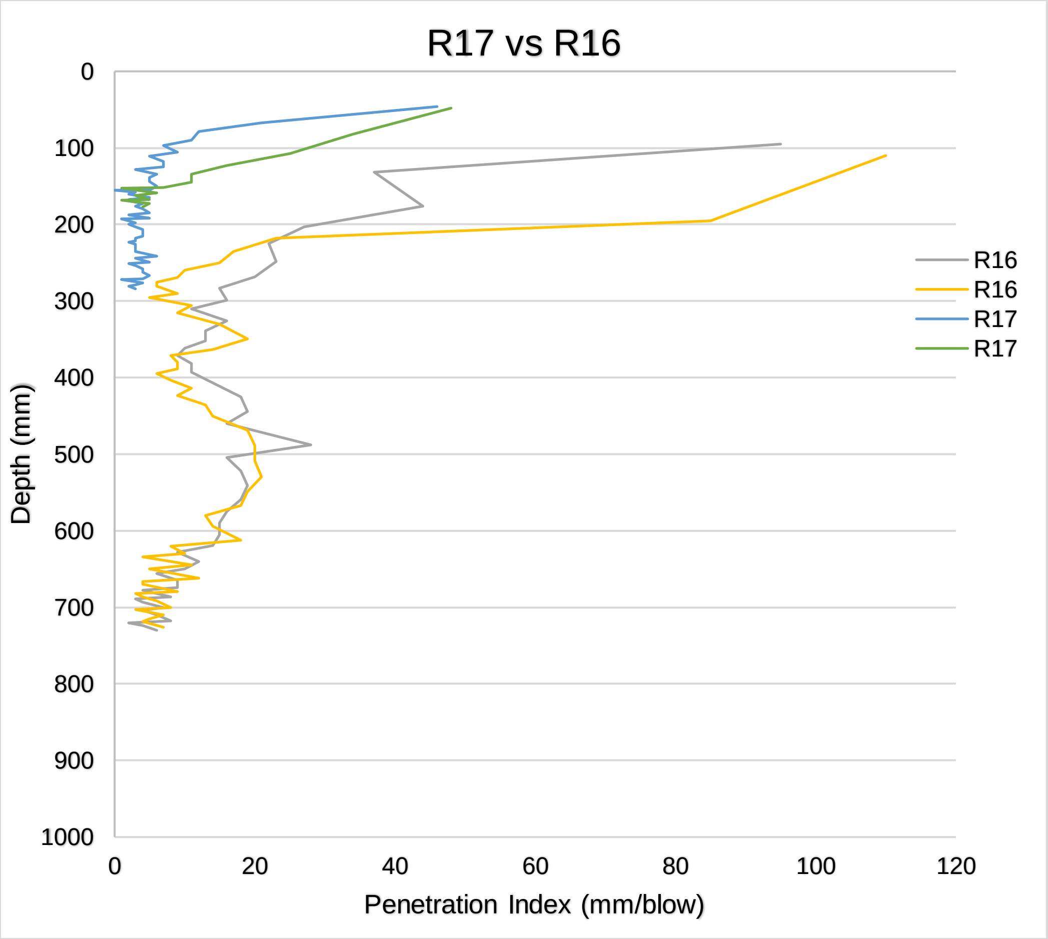


Figure 5.13: R16 and R17 penetrometer measurements compared.

Water infiltration and root penetration will be much better at R16 and will provide a better medium for plant growth, even though the fertility is lower than at R17. It can be concluded that for these two sample locations, plant growth was more affected by physical conditions than fertility.

5.4 Conclusion

The soil physical and chemical measurements reported in this chapter, indicate the high variability of soil conditions in this Rehabilitated Field, and the yields of weeds, which are less sensitive to deficient conditions than arable crops, clearly indicate that this soil variability is evident in weed growth. Knowledge of this variability is key, and while for commercial cropping purposes, this makes this site less suitable, for research purposes this makes the current site ideal, as it is important to ascertain under what conditions rehabilitated fields will be irrigable and productive, and under what conditions they will not be suitable for irrigated cropping.

Good correlations between phosphate and organic carbon were observed. Fertilizer application can be expected to improve overall fertility and can assist in addressing the high variability in the Rehabilitated Field.

Results also indicated that sites with higher fertility resulted in lower yields when a restriction layer was present, compared to sites with lower fertility but no restriction in physical conditions. Weed growth was more affected by the physical conditions of the soil than fertility. For most of the sites, when physical and chemical conditions were compared, physical conditions seemed to be the more limiting factor affecting weed yield. This signifies the importance of management during rehabilitation and following the guidelines created as this is when most of the physical problems occur.

The potential to use rehabilitated land for irrigation using mine water will be a major factor in determining the widespread adoption of this gainful use of mine water, and future evaluation of cropping on this site will assist materially in setting the criteria needed to determine if a particular rehabilitated land is suitable for irrigation.

The next chapter covers a widely used system to classify the productive capability of rehabilitated land and an assessment of its use in determining the irrigable potential of rehabilitated land.

Chapter 6: Use of a dryland classification system to predict the suitability of rehabilitated land for irrigation

6.1 Introduction

Currently, there are no guidelines available to rehabilitate mined land to an irrigable standard. With thousands of hectares that still need to be rehabilitated in Mpumalanga alone, this is a noteworthy opportunity to increase land availability for high-potential agriculture.

According to SABI (South African Irrigation Institute), there are a number of factors that must be taken into consideration when soils are investigated for irrigation purposes. This includes factors like soil depth, texture, structure, chemistry and colour. With the assistance of Bruce McLeroth from Red Earth Consulting, these factors were measured, analysed and incorporated into field maps to assist with identifying the land capability of the rehabilitated area and its suitability to predict irrigable potential. Good infiltration and internal drainage are crucial for good irrigable potential and these are mainly linked to soil texture and structure.

SABI states that any soil with a depth of 900 mm or more meets the soil depth requirements for irrigation and is most likely to be irrigable, depending on the soil surface type, soil chemistry and texture. Soils as shallow as 450 mm can also be irrigated, but good irrigation management and crops with a shallower rooting depth are recommended.

This chapter mainly focuses on outlining methods used to survey soils of the rehabilitation area, the outcomes of the survey and thereafter a discussion regarding the suitability of this methodology for defying the suitability of a rehabilitated site for irrigation. Possible shortcomings in the current classification systems used are also identified and discussed.

Findings from this chapter were used to identify sampling points used in Chapter 7 to determine what influences the irrigability of rehabilitated land.

6.2 Dryland classification system for rehabilitated land

With the assistance of Bruce McLeroth, from Red Earth Consulting, a full standard rehabilitation soil survey was done to determine the land capability of the Rehabilitation Field for arable use. The system as used by Red Earth cc has been widely used in South Africa to determine the land use capability of rehabilitated land.

A soil sampling grid of 50 m x 50 m was used in the Rehabilitation Field. For each point on the grid, auguring was conducted using a 100 mm bucket auger to a maximum depth of 1.8 m, or less if impenetrable. Figure 6.1 displays the 50 x 50 m grid at the Rehabilitated Field.

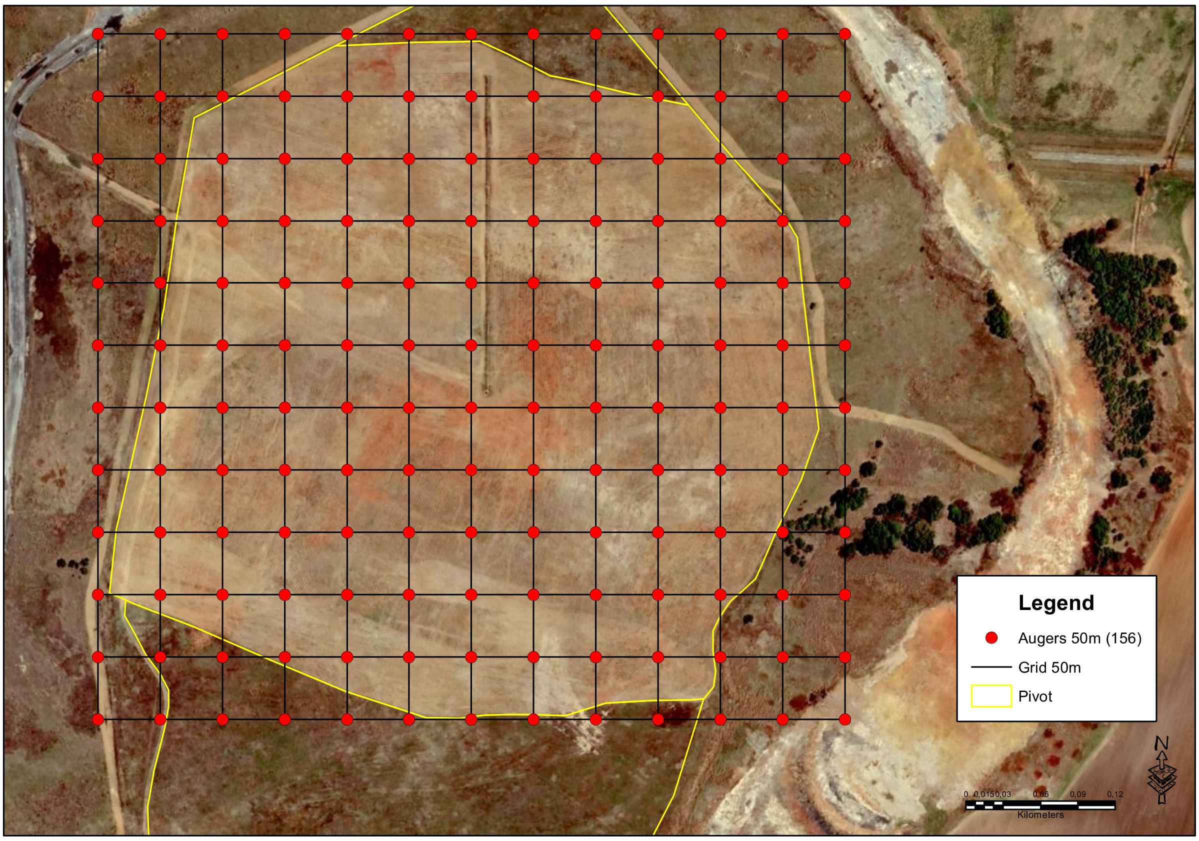


Figure 6.1: 50 m x 50 m sampling grid at the Rehabilitation Field.

Data recorded included horizon name, depth, clay plus silt content estimate, sand grade estimate, colour code (according to the Munsell Colour Chart), saprolite weathering status, structure, seasonal wetness hazard, cultivation factors and compaction/hard-setting. Figure 6.2 represents one of 120 soil auger points investigated in the Rehabilitated Field.

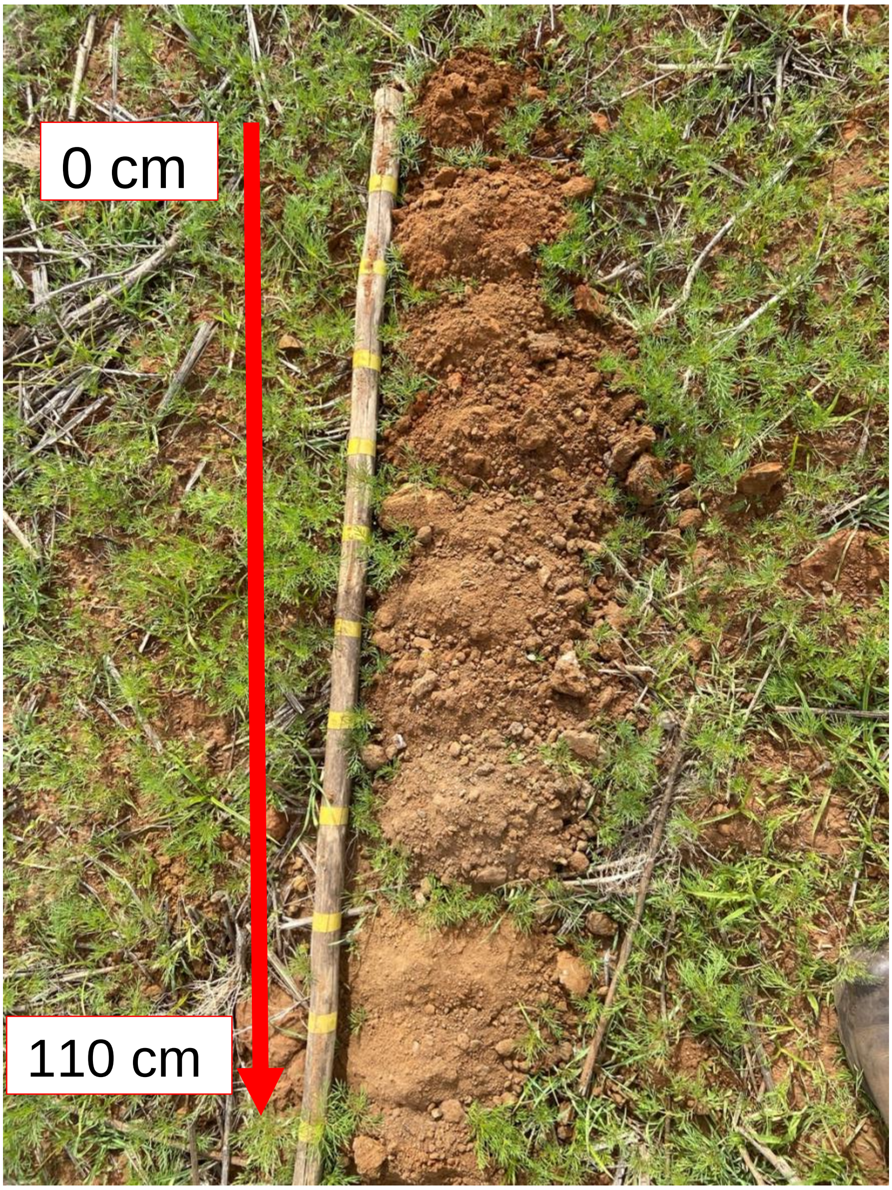


Figure 6.2: Soil extracted by auger at a single point from depths of 0 - 110cm.

After the soil surveying exercise, maps were created from the results obtained from the Rehabilitated Field. The maps were produced at a 1:5000 scale that included the following:

1. Soil Cover Maps:
   - soil depth
   - effective rooting depth (soil)
   - cover soil type

These three maps were used to create the final land capability map. The post-mining land capability map includes arable, grazing and evolving wetland classes.

Soil depth is an important aspect that determines arable potential. Drainage past the root zone is crucial and is influenced by soil depth. In high-rainfall areas, drainage well past the root zone is required. If not, a perched water table can form that may result in salinization of the root zone. With poorly rehabilitated areas, great variability in soil depth can be expected. The published mine land rehabilitation guidelines state that a soil reserve should be kept for amendments as necessary after rehabilitation. If this is not done, soil depth is very expensive to increase once the rehabilitation process has been completed. Figure 6.3 represents a depth-to-spoil map (soil depth) of the Rehabilitated Field. The blue line in Figure 6.3 represents the irrigation pivot at the time the analysis was done and the double brown line the road to the centre of the pivot.

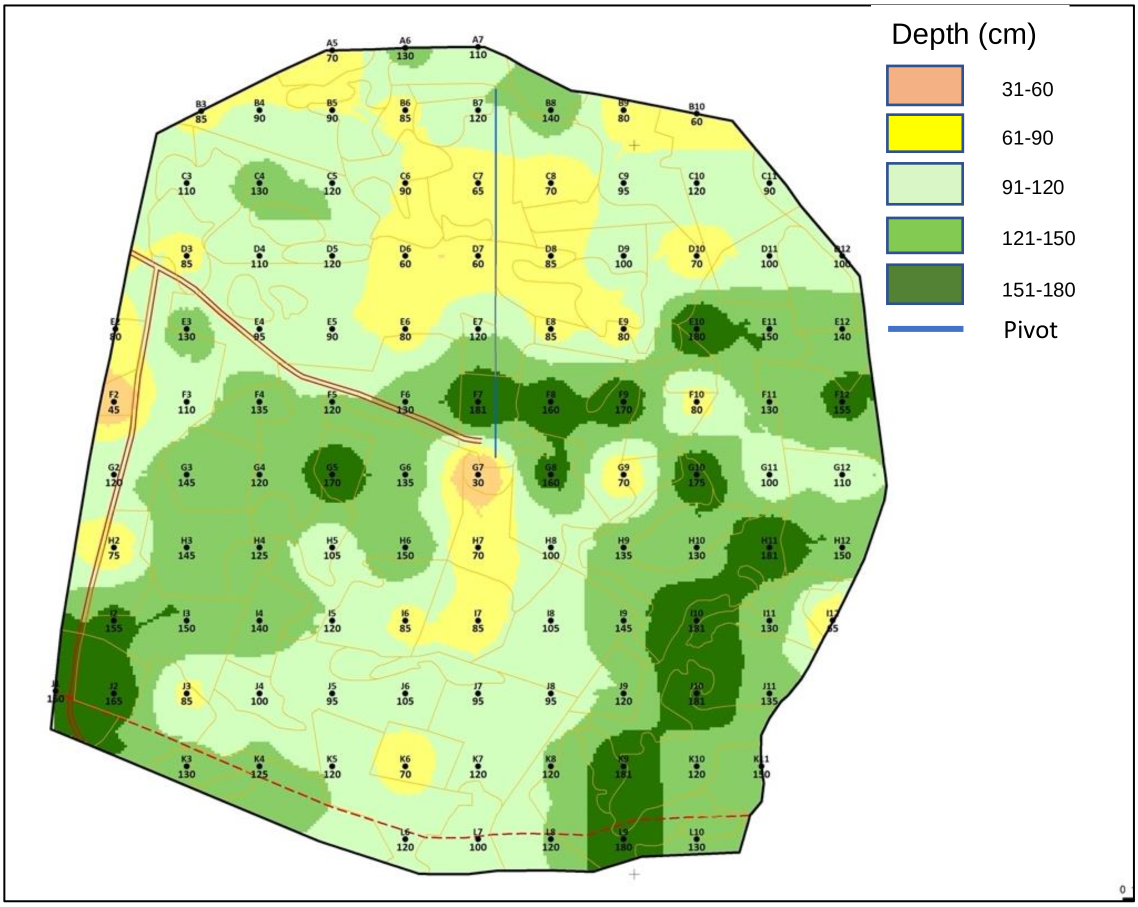


Figure 6.3: Soil to spoil depth at the Rehabilitated Field.

The variability in soil depth at the rehabilitated field is clearly visible. More than 70% of the Rehabilitated Field has a soil-to-spoil depth exceeding 900 mm, with less than 25% of the field having a depth ranging between 600 mm and 900 mm. Figure 6.3 indicates that at least 70% of the Rehabilitated Field meets the SABI requirement of sufficient soil depth to be classified as irrigable.

Effective rooting depth (ERD) is limited by plant morphological characteristics or the depth of un-compacted soil, and in the case of rehabilitated mine-land, underlying spoil material is frequently relatively loose, or saprolitic material is incorporated within the rocky sub surface matrix which can provide a medium that supports root growth. ERD determines the volume of soil that roots can explore to extract water and nutrients. Under dryland conditions, this may be the most important yield potential determining factor.

Soil texture can determine the root zone water holding capacity. The Rehabilitated Field at Mafube consisted of more coarse material than was found with the unmined soil in close proximity. According to the USCS (unified soil classification system) coarse sand can be defined as particles ranging between 4 mm and 0.074 mm. Coarse material may improve the infiltration of water in the soil, which can be beneficial where restricting layers and compaction are present like in the rehabilitated area, but, too high content of coarse material decreases the water storage potential of the soil. Figure 6.4 indicates the ERD map created for the Rehabilitated Field. The ERD was determined by subtracting the percentage of coarse material from the soil depth of the profile. This map, therefore, rather presents an indication of water storage potential that affects arable potential, and is perhaps not aptly named in the classification system. Irrigable potential is expected to be less affected by the water storage potential, especially if high frequency irrigation is possible, as is the case with centre pivot irrigation.

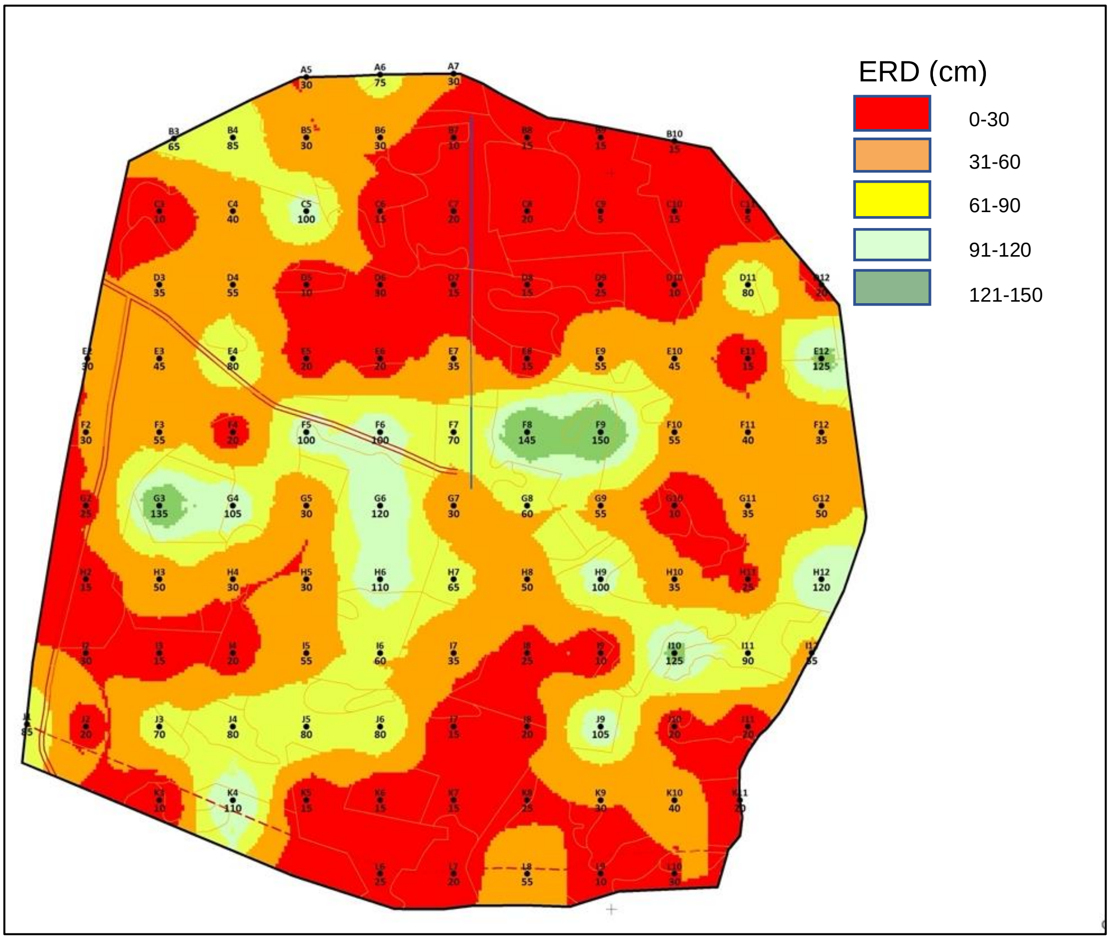


Figure 6.4: Effective rooting depth at the Rehabilitated Field.

As shown in Figure 6.4, the “water storage potential” varies over the rehabilitated field, and this would most likely result in variability in crop growth over the area under dryland conditions. The map in Figure 6.4 is expected to affect irrigable potential differently, as the water in the profile can be easily maintained with irrigation. This shows the opportunity for irrigation to provide more optimum soil conditions for growth and thereby obtain higher yields than under dryland conditions.

Soil cover types for rehabilitated fields tend to exhibit greater variability than undisturbed fields. Better rehabilitation practices will result in lower variability and more uniform soil cover. Table 6.1 represents the range of cover soil types and Figure 6.5 the distribution of the cover soil types over the rehabilitated field.

Table 6.1: Cover soil types at the Rehabilitated Field

COVER SOIL TYPES (INDICATED RANGE)			
Code:	**Description:**	**Code:**	**Description:**
Kr	Kandic red	Ky	Kandic yellow
Ny	Neocutanic yellow	Ni	Neocutanic intermediate
P	Plinthic	Nd	Neocutanic dark
G	Gleyic	Sy	Saprolitic yellow
		Sg	Saprolitic grey

Each soil type has its own unique characteristics, which differ in physical and chemical properties, contributing to the high variability of the field.

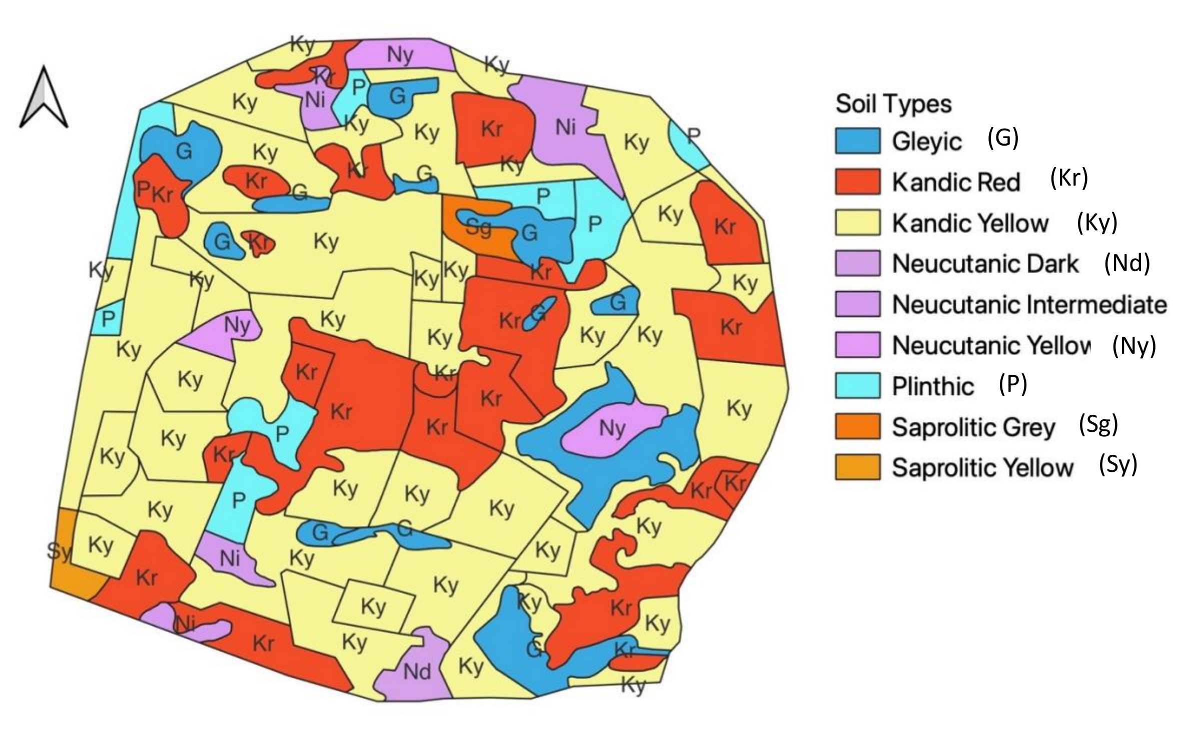


Figure 6.5: Soil cover types at the Rehabilitated Field.

Infiltrability and soil chemistry vary for each soil cover type and react differently to climate and irrigation conditions. Soil structure that is stable in water, in other words not dispersing, is preferable, or else soil crusting can develop. Fine textured soil, such as high silt or clay soils, are vulnerable for crusting to occur.

The areas marked in dark blue (gleyic), in the map in Figure 6.5, are areas where a G-horizon was placed on the topsoil. This will definitely limit water infiltration in that specific area and will most likely result in waterlogged topsoil, restricting aeration and water infiltration into the soil. Low growth and yield potential are expected from these areas.

Waterlogging is expected to be more of a problem in the high-rainfall summers than in the dry winters. Most gleyic areas were created when soil was trucked in after the rehabilitation process to fill up depression areas. In all of the gleyic areas, Ky (kandic yellow) soil was found beneath the top horizon, which is a lot more suitable for arable and irrigable conditions.

A map illustrating the arable land capability of the Rehabilitation Field was created by combining the soil cover type map and the ERD map. Table 6.2 illustrates the land capability classes and descriptions for each class for the dryland classification.

Table 6.2: Land capability classes at the Rehabilitated Field

LAND CAPABILITY (REHABILITATED)						
Map Notation	**Description**	**Explanation**	**Area**			
			ha	**%**	**ha**	**%**
A	Arable	AERD > 60 cm	12.50	48.49	14.86	57.64
A-G	Arable - transitional Grazing	AERD 60 - 40 cm	1.90	7.37		
A-Wh.sp	Arable - transitional Wetland Human (soft plinthic)	AERD > 60 cm. Plinthic (soft plinthic B-horizon - with raised clay content - may prevent/limit rooting to deeper horizons) in top 40 cm [Arable]	0.46	1.78		
G	Grazing	AERD 25-59 cm	5.21	20.21	5.21	20.21
Wh.sp-G	Wetland Human (soft plinthic) - transitional Grazing. i.e. Man-Made Wetland	AERD 25-59 cm. Plinthic (soft plinthic B-horizon - with raised clay content - may prevent/limit rooting to deeper horizons) in top 30 cm [otherwise Grazing]	1.11	4.31	2.24	8.69
Wh.sp-A	Wetland Human (soft plinthic) - transitional Arable. i.e. Man-Made Wetland	AERD > 60 cm. Plinthic (soft plinthic B-horizon - with raised clay content - may prevent/limit rooting to deeper horizons) in top 30 cm [otherwise Arable]	1.13	4.38		
Wh.gc	Wetland Human (gley). i.e. Man-Made Wetland	ERD < 30 cm. Gleyic (G-horizon) in top 30 cm [will definitely prevent/limit rooting to deeper horizons; so AERD not indicated]	3.47	13.46	3.47	13.46
TOTALS			**25.78**	**100**	**25.78**	**100**

* AERD – Arable effective rooting depth

Figure 6.6 represents the land capability map for the Rehabilitated Field. Soil cover type contributed the most towards the capability classes, except where soil depth or ERD showed signs of high clay content in the top 0-60 cm layers, thus creating a duplex soil profile. Duplex soils occur when there is an abrupt change in texture between layers. The abrupt change can either be from low levels of upper horizon clay to high levels of lower horizon clay, or the other way around. It is the change in texture that reduces the ease of water flow across the horizon change. Duplex soils are in most cases not suitable for irrigation because of the low infiltration rate caused by the subsoil layers. The legend in Figure 6.6 is described in Table 6.2.

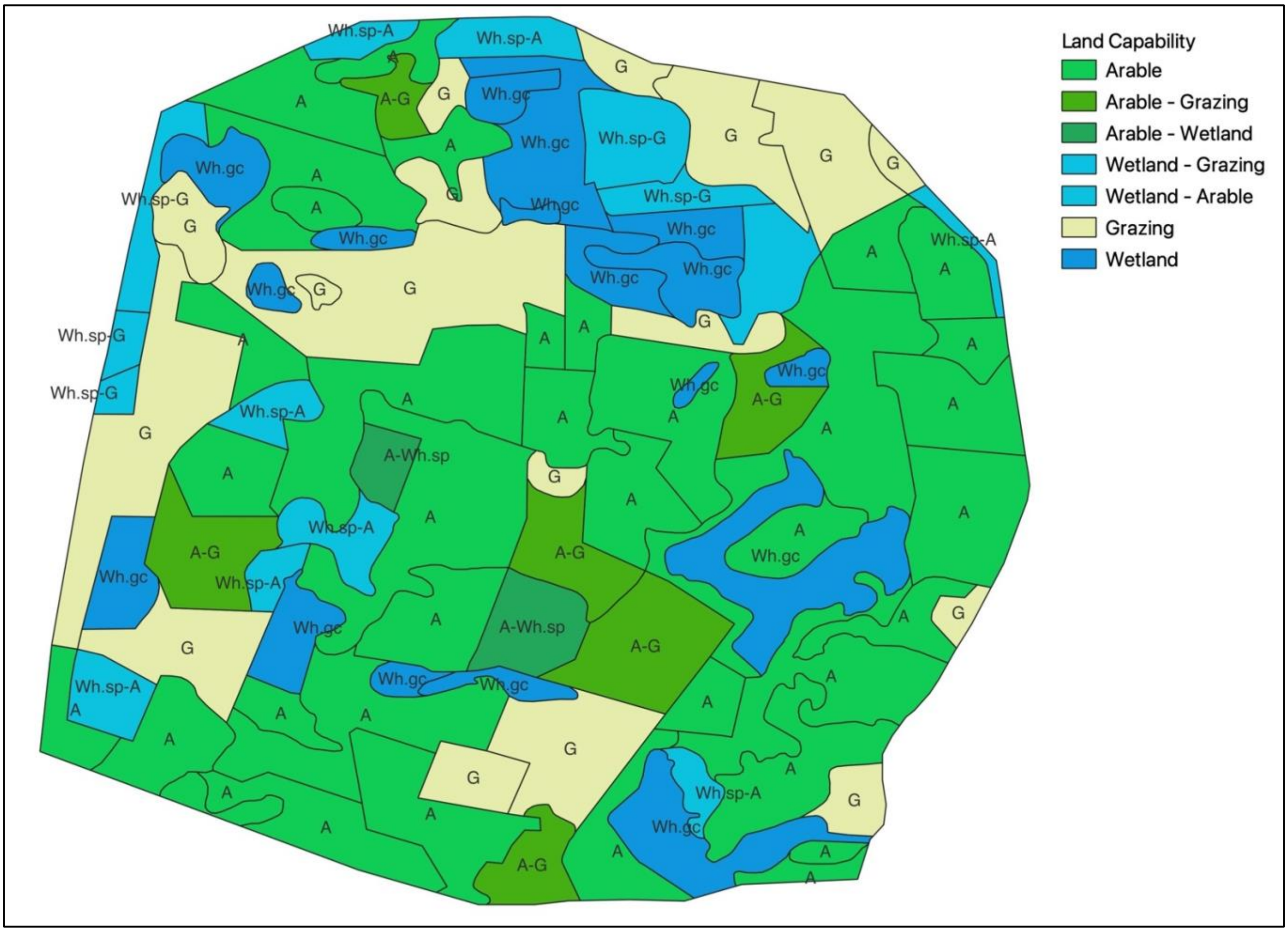


Figure 6.6: Land capability map of the Rehabilitated Field

The map in Figure 6.6 indicates the land capability according to arable standards where 57% is regarded as arable, and 20% as grazing. Only 13% of the field is classified as problematic where water infiltration and root penetration will be very limited. This is due to the high clay content (G horizon) on the surface, where water infiltration is expected to be poor. This can create a layer with very low hydraulic conductivity which will restrict water infiltration.

Water must first enter the soil for it to be of value. The rate at which water infiltrates into the soil is the infiltration rate (mm/hour). Water movement in the soil largely depends on the size of the micropores. In general, larger pore sizes result in higher infiltration rates. When the precipitation rate (rainfall or irrigation) is higher than the infiltrability of a soil, runoff or surface ponding can occur.

It is important to remember that land classified as arable is not necessarily irrigable. Irrigable and arable land capability is expected to be different in the rehabilitated field. The land capability map is derived from soil properties that relate to the potential for arable production. Infiltration and good drainage are crucial properties for both dryland and irrigation, but are determining factors for irrigable site selection.

6.3 Conclusion

The land capability classification survey conducted at the Rehabilitated Field, as expected, also identified a great degree of soil variability. The maps were created from valuable detailed data regarding soil depth, texture, and type, and clear boundaries between different soil capabilities were drawn.

The land capability map indicates that variability in crop growth can be expected at the Rehabilitated Field. Soil depth requirements for irrigation appear to be more than sufficient. Only 13% of the area was classified as low potential arable land, these were the areas that had a G horizon on the surface. A low infiltration rate is predicted for these areas which could affect production under dryland or irrigated conditions. The ERD estimation of Red Earth Consulting can rather be defined as the water storage potential of the soil. This is because coarse material in the profile does not necessarily restrict root growth, but rather affects the water-holding capacity of the soil. In rehabilitated soils, roots may often penetrate the underlying spoil. Water holding capacity is more of a limiting factor for dryland conditions than irrigation. The areas in the land capability map classified as lower potential land (grazing) due to a low ERD may be suitable for irrigation as coarse material in the surface of the profile can increase infiltrability. This was one of the hypotheses that was tested in the next chapter.

There were two possible issues or shortcomings identified with the dryland classification methodology to predict the suitability of a site for irrigation. Firstly, the topography of the area is an important factor in determining the irrigable potential. Especially in rehabilitated areas where secondary subsidence is likely to occur within a few years after initial rehabilitation. Topography greatly affects water flow pathways and areas prone to ponding may develop. Describing surface flow paths from the topography of an area can be regarded as the first step in determining the suitability of an area for irrigation, and this is not considered in the production potential assessment described above.

The second shortcoming identified was restricting layers in the profile. Compacted layers in the profile are expected to affect root growth, infiltration and drainage. The penetrometer is a useful tool to identify restricting layers in the profile. Adequate ripping should decrease the effect of compacted layers in the profile.

Results of this chapter were used to classify monitoring points into different categories that are used in the next chapter to determine what influences the irrigability of the Rehabilitated Field.

Chapter 7: Determining what influences the irrigability of rehabilitated land

7.1: Introduction

The irrigable potential of rehabilitated land can best be assessed by monitoring actual crop growth and soil response to irrigation. It was, therefore, necessary to establish a crop under irrigation in the rehabilitated field to monitor. The results from this chapter are also used to determine to what extent the dryland classification system considered in Chapter 6 can be used to define the suitability of a rehabilitated area for irrigation.

Growth and yield were monitored and used to assess the effect of variability in soil properties and the final topography after rehabilitation, on crop growth. Chemical analysis of the soil for each monitoring site was needed to include soil fertility as a factor. The aim was to determine if chemical or physical properties, or both were responsible for the results obtained. Although mine water was used for irrigation, no change in soil properties were expected in the first six months of irrigation, but the soil analysis from Chapter 3 could be used as the initial soil data for future monitoring. Because fertility is easier to manage by applying nitrogen and phosphorus and irrigation with a circum-neutral water rich in potassium, major differences in plant nutrition were not expected.

Data analysed from these measurements and monitoring sites played a key role in answering the two main questions posed. “What defines the irrigable potential of rehabilitated areas?” And, “Can a dryland classification system commonly used in the mining industry also be used to define irrigability?”

The outcomes of this study will assist in the development of guidelines for mine land rehabilitation to irrigable potential. They will also highlight additional work needed to improve rehabilitated areas classified as arable, but that perform poorly under irrigation, to achieve an irrigable classification.

The outcomes of the dryland classification system discussed in chapter 6 were used to identify sampling locations to test the suitability of this approach to define irrigable potential of rehabilitated areas.

7.2 Crop establishment and sampling methodology

This section includes the establishment of a crop under irrigation and the sampling methodology used.

The pivot only became fully functional in March 2022, and this was the first opportunity for soil preparation and seeding to commence for commercial scale mine-water irrigation trials on rehabilitated land at Mafube. Our commercial maize farming partner was not prepared to risk incurring a loss with maize production on this field, as input costs are very high, and yields from rehabilitated fields are expected to be lower. In addition, he was concerned that the ripping that was required to alleviate compaction, may have brought boulders close to the surface that could damage his expensive equipment, and it was just not a worthwhile value proposition for him. For this reason, the research team and mine management were responsible for cropping this field Although adequate ripping was never completed and only small areas were covered due to breakdowns and the high cost of renting the machinery. For ease of management, and to avoid having to cultivate and seed this field each year, it was decided to plant a perennial pasture mixture, in the hope that once the field had settled in and the pivot had been proven reliable, that the commercial farmer may be prepared to take over the management of this site, either with the pasture or possibly as an additional irrigated maize field.

The mixture selected consisted of lucerne and fescue, both high value forage crops for animal production when harvested or grazed. Lucerne, (*Medicago sativa*), is a summer crop and a dormancy class 7 was planted. The dormancy class determines the length of the growing season. In South Africa, dormancy classes between 5 and 10 are the most suitable, where dormancy class 5 is semi-dormant and class 10 is strongly non-dormant. Dormancy class 10 can also be referred to as winter active. Dormancy class 7 is classified as having intermediate dormancy, which will allow growth in the highveld area from September until May. Lucerne, a leguminous crop, lays dormant during the cold winter months, but fescue (*Festuca arundinacea*) is a temperate grass crop that thrives at cooler times of the year. The combination of these two pastures results in a permanent green canopy cover throughout the year, and this is expected to maximise the amount of irrigation water needed. Irrigating throughout the year is a very beneficial and sustainable method of utilizing as much mine water as possible. Typically, winter crops use more irrigation water than summer crops do because this is the dry season in the summer rainfall region, and most of the crop's water requirement needs to be supplied by irrigation (Annandale et al., 2019). An added and very important benefit of including dry and wet season irrigation for most mines, is that much less water storage is needed to hold mine water between supplemental irrigated, summer seasons.

Lucerne is a deep-rooted, perennial pasture, with a strong and aggressive rooting system. Due to its deep roots (> 2 m on suitable soils) and high water use, it can access rising water tables and possibly temporarily water-logged soils, but generally, this crop is not favoured by permanently wet soil conditions, like waterlogged soils (Smethurst et al., 2005). Lucerne roots are also more likely to penetrate deeper through compacted layers than most other crops, thereby possibly increasing infiltration, deep drainage and assisting with alleviating compaction in the upper soil layers. Fescue has an extensive rooting system, but shallower than lucerne. Fescue / lucerne mixtures are common in areas with cold winters (Koc et al., 2004). Due to different rooting depths and systems, competition for water and nutrients between the crops is not expected. Both fescue and lucerne produce high yields under irrigation, and also have a relatively high drought tolerance and can survive longer dry periods than most other crops.

Soil was cultivated in March 2022 as shown in Figure 7.1. Seeding occurred directly after cultivation, shown in Figure 7.2. The planting mixture consisted of the following:

- Lucerne (*Medicago sativa*): Lima Grain, WL 458 HQ, dormancy 7, 15 kg/ha
- Tall Fescue (*Festuca arundinacea*): Lima Grain, Charlem, 20 kg/ha
- Fertilizer: Kynoch, MAP, 140 kg/ha

Figure 7.1: Soil preparation at the Rehabilitated Field

Figure 7.2: Planting of the seed mixture and fertilizer application at the Rehabilitated Field

Seeding was completed in three days. Unfortunately, heavy rain occurred a week after seeding which was not ideal for germination of the lucerne. Table 7.1 shows the recorded rain at the site, with severe ponding occurring in some areas with a detrimental effect on germination.

Table 7.1: Rain recorded at the Rehabilitation Field site in the first three weeks after planting

Date	**Rain**
	mm
2022/04/04	40
2022/04/09	30
2022/04/11	10
2022/04/12	25
2022/04/13	25
2022/04/26	14
Total	144

Even with good soil conditions where drainage and infiltration are optimum, a total of 144 mm of rain will not be ideal and will most likely result in ponding or runoff. Figures 7.3 and 7.4 show ponding areas that were still present in the rehabilitated field, long after the heavy rainfall. Germination is also visible in Figure 7.3 around, but not within, the ponded areas.

Figure 7.3: Ponding at the Rehabilitation Field

Figure 7.4: Water ponding due to surface subsidence and insufficient filling

The ponding visible in Figure 7.4 was present for a long period of time, and whilst irrigation was at times necessary for the rest of the irrigated field, this continuously added water to ponded areas, further limiting germination in these low-lying areas.

Since lucerne, which is a perennial crop, requires 6 to 12 months to become well established, and some weeds and volunteer crops establish more rapidly than this, it is normally prudent to reduce weed pressure by mowing the pasture in the early stages of establishment. This is usually done after winter and is referred to as a “winter cut”. This was carried out from 1st to 3rd October 2022. Figures 7.5 and 7.6 show the winter cut at the Rehabilitated Field.

Figure 7.5: Winter cut at the Rehabilitated Field, early October 2022


Figure 7.6: Remnants of volunteer small grain regrowth cleared with the winter cut, early October 2022.

Some wheat and other temperate small grain crops germinated from previous failed attempts at establishing crops due to irrigation system challenges, and this was also removed with the winter cut, as can be seen in Figure 7.6. The previous attempt to produce a crop under irrigation on the Rehabilitated Field was eventually aborted after multiple challenges occurred with the irrigation system. These challenges were mainly related to water availability and theft at the pivot. The regrowth of volunteer small grains in the warm season was, as expected, poor, giving the lucerne / fescue mixture an ideal opportunity to establish. With each subsequent hay harvest , the weed population should decrease and the pasture should become more dominant.

The growing period between each harvest usually varies between 6 to 8 weeks, depending on weather and soil conditions. The first commercial hay harvest was scheduled for the first week of December 2022, but due to heavy and continuous rain throughout the month, mowing was delayed. However, the site was accessible by foot and plant samples were taken 6-7 December 2022.

Sampling methodology

Most of the sampling points were situated in the same location as the weed growth sampling points in Chapter 5. By adding an extra set of data to the sampling points, a better understanding of system behaviour should be achieved.

A total of 21 sampling points (Figure 7.7) were identified and classified into different classes within the Rehabilitated Field. The five classes showed in Figure 7.7 are explained in the next section.

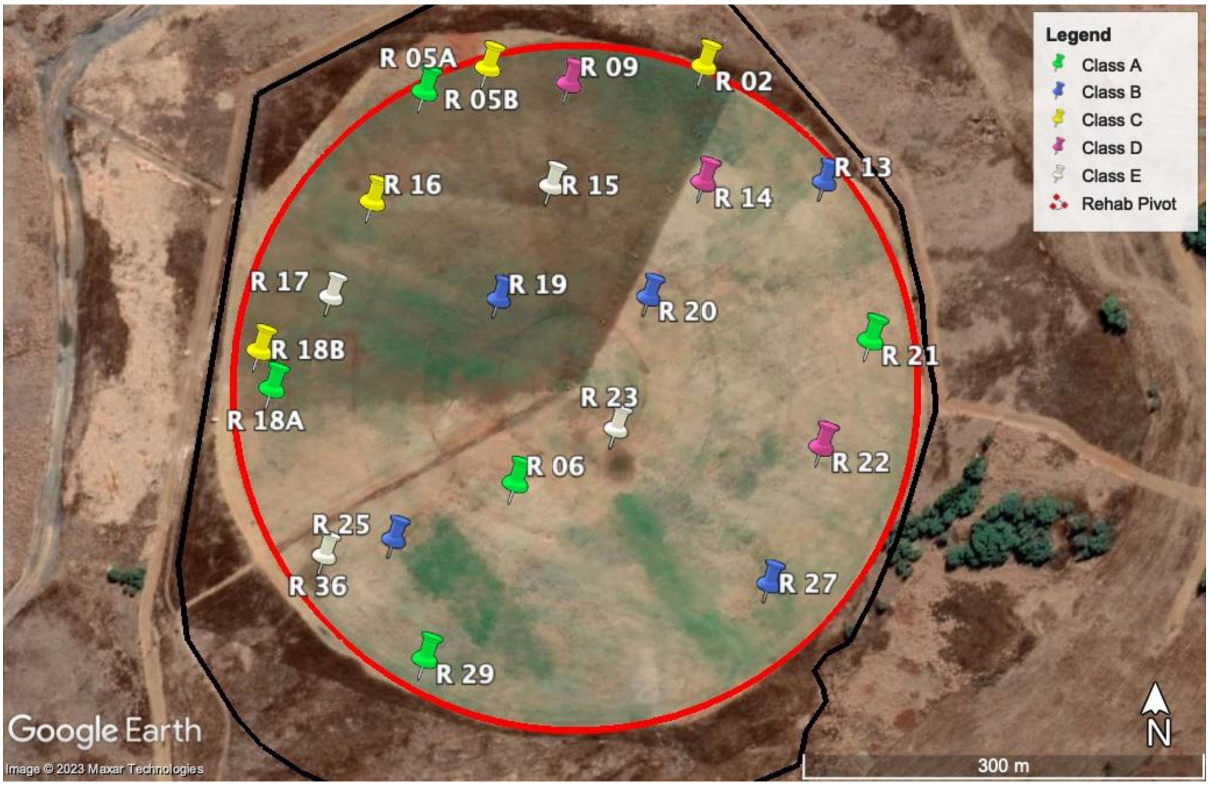


Figure 7.7: Sampling points classified in five irrigability classes at the Rehabilitated Field.

Figure 7.8 illustrates the monitoring undertaken at each point, which included taking the following samples:

- Three 1 m^2 samples of plant material growth, cut at 7cm above ground level.
- 0-300 mm soil samples from the centre of each of the 1 m^2 sampling squares and mixed to obtain a single soil sample per site.
- Leaf area index (LAI) at each sampling square.

The LAI was measured using the ACCUPAR LP-80 PAR/LAI ceptometer. Three readings per square were taken, before the material was harvested, giving a total of 9 readings per site. The LP-80 measures photosynthetically active radiation (PAR) and uses the reading to estimate LAI for the plant canopy cover.

Soil samples were sent to Nvirotech Laboratories for the following analyses:

Fertility (pH water and Bray II for P);

Micro nutrients - Zn, Cu, Mn, Fe (Mehlich III)

Particle size fractions- Clay, silt and different sand fractions

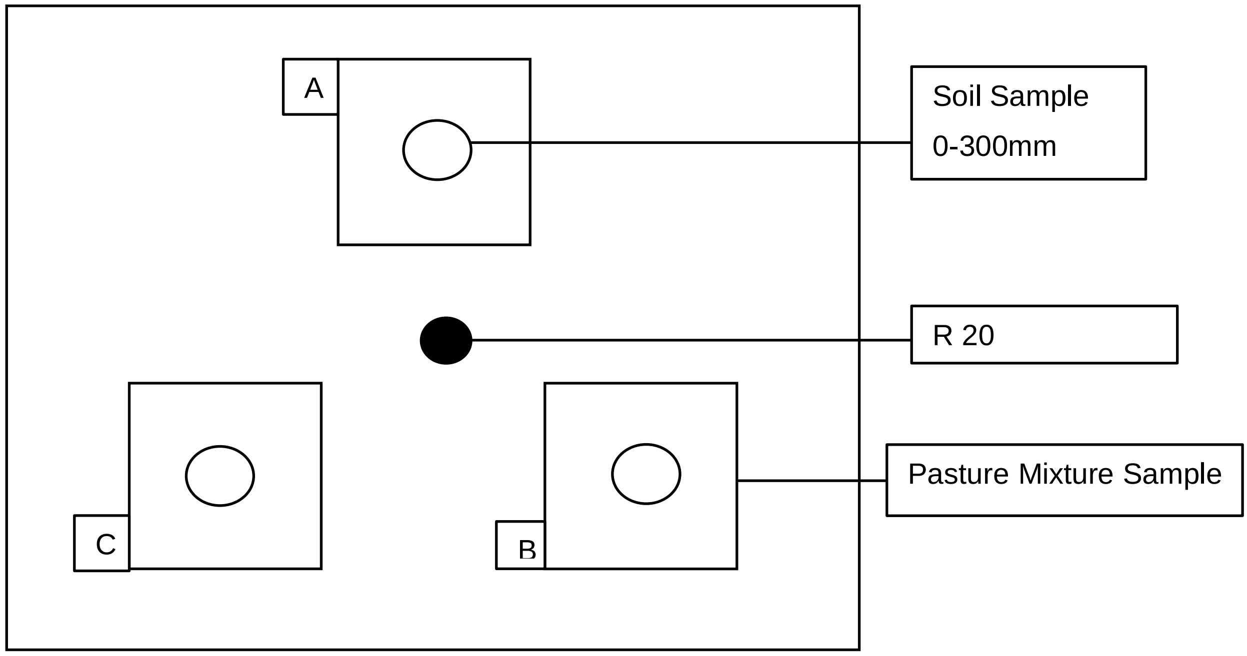


Figure 7.8: Sampling regime for Rehabilitated Field monitoring sites (R 20 as example)

The sampling square had a short 7 cm long rod at each corner on which the square could rest to keep it just off the soil surface. This ensured that all samples were harvested 7cm above the soil surface. The material above the square was harvested using a 2-stroke, petrol powered hedge trimmer. Figure 7.9 shows the sampling square where the material still needs to be raked up and collected after being cut. Samples were collected and dried at 65 °C for 72 hours before being weighed.


Figure 7.9: Hedge trimmer and sampling square.

The sampling method used was not ideal, but due to the study period that was coming to an end, it was not possible to wait for better establishment of the pasture. However, the data obtained from the samples was still sufficient to produce a good initial estimate of the spatial variability of the field.

7.3 Results and discussion

Table 7.2 presents yield and LAI measured at the sampling points. The yield results for each sub-sample and the combined average for each monitoring point are presented. The average LAI is also included. Sampling points R23, R15 and R17 were situated in waterlogged areas which restricted access for measurements and sampling.

Table 7.2: Pasture yield and LAI measured at the sampling points (December, 2022)

Sample	A	B	C	Average	Average LAI
	t/ha	t/ha	t/ha	t/ha	
R 21	3.17	3.3	3.5	3.3	5.1
R 29	3.5	3	2.1	2.9	2.7
R 05A	2.8	1.2	1.8	1.9	2.4
R 18 A	1	1.3	1	1.1	0.6
R 06	1.7	2.3	1.7	1.9	2.3
R 20	2	1.5	1	1.5	1.1
R 25	0.8	1.3	1.1	1.1	0.3
R 13	1.4	0.8	0.8	1.0	1.2
R 19	1.4	2	1	1.5	1.1
R 27	1	0.6	0.6	0.7	1
R 02	2.8	3	2.3	2.7	3.7
R 05B	3.3	3.2	2.9	3.1	4.2
R 16	2.6	2	1.6	2.1	1.5
R 18B	1.9	1.9	21	2.0	2
R 09	0.7	0.6	0.7	0.7	0.1
R 14	0.7	0.9	1.1	0.9	0.2
R 22	2.7	1.9	2	2.2	2
R 23	-	-	-	-	-
R 36	0.2	0.3	0.2	0.2	0
R 15	-	-	-	-	-
R 17	-	-	-	-	-

Unfortunately, the soil samples collected were contaminated by the laboratory and would not have indicated accurate data that represent the different sampling locations. By the time this was discovered, it was too late to retake samples as other work like cutting and fertilizer applications had already occurred on the site. However, it was not expected that large differences would have been apparent between samples taken before planting and after a short growth period. This will become more important in future, as several seasons of irrigation with mine water will likely result in large differences developing.

Classification of sampling sites

Certain soil physical conditions and hydrological position in the landscape are expected to be important determining factors of the irrigable potential of the Rehabilitated Field. These were not explicitly included in the rain-fed rehabilitated site classification system used by Red Earth Consulting. Restricting layers due to compaction, and depression areas caused by subsurface subsidence, creating surface ponding and waterlogged areas, are expected to significantly affect irrigable potential.

Restricting layers in the Rehabilitated Field were identified using a penetrometer, as was explained in Chapter 5. Downward movement of water and roots are minimised by restricting layers in the soil. The penetrometer results along with those from the dryland classification system (Chapter 6) were used to categorize the sampling points into different irrigability classes (A to E). These classes were used to identify factors that influence the irrigability of the rehabilitated field. These classes are represented in Table 7.4. The second column consists of the dryland capability classification from Chapter 6, the third column displays irrigability, and the last column in the table lists the main reason(s) for the irrigability prediction.

Class A refers to areas where good arable and irrigable potential are expected.

Class B indicates areas where the topsoil and subsoil were identified as being good for arable conditions during the dryland evaluation. However, penetrometer measurements indicated compacted layers in the profile to an extent where resistance in downward movement of water and roots are expected and therefore, classified as being of moderate to poor suitability for irrigation. If the problem of the restrictive layer in the soil can be addressed, then the suitability for irrigation may improve for the area.

Class C refers to areas that were classified as grazing under the dryland classification system due to poor water-holding capacity. However, these were classified as a good area suitable for irrigation, as water can be applied frequently with an appropriate irrigation system, and the soil profile does not need to have a large water storage capacity for crops to overcome dry spells. Due to the higher content of coarse material in the surface of the profile, water infiltrability is expected to be high.

Class D represents areas where both dryland and irrigation suitability are classified as poor. These are the areas that were covered with gleyic material to fill up depression areas and has a surface zone problem. Low water infiltration is expected due to the high clay content associated with gleyic soils. Gleyic soils are commonly found in wetlands and are not suitable top soils for crop production. These areas are classified as unacceptable for irrigation.

Class E represents sites located in areas prone to ponding. Very poor crop growth is expected in these areas, and water-logged soil conditions were expected and observed throughout most of the year.

Table 7.4: Sampling points categorized into different classes to define what is expected to influence the irrigability of the rehabilitated land

Site	Dryland Classification	Irrigability	Irrigability Classification Reason
Class A			
R 21	Arable	Good	No Restrictive Layer
R 29	Arable	Good	No Restrictive Layer
R 05A	Arable	Good	No Restrictive Layer
R 18A	Arable	Good	No Restrictive Layer
R 6	Arable	Good	No Restrictive Layer
Class B			
R 20	Arable	Moderate	Layer (30cm), compacted profile
R 13	Arable	Moderate	Layer (30cm), compacted profile
R 25	Arable	Moderate	Layer (30cm), compacted profile
R 19	Arable	Moderate	Layer (30cm), compacted profile
R 27	Arable	Moderate	Layer (35cm), compacted profile
Class C			
R 2	Grazing	Good	Good surface infiltration expected
R 05B	Grazing	Good	Good infiltration, no layer
R 16	Grazing	Good	Good surface infiltration expected
R 18B	Grazing	Good	Good surface infiltration expected
Class D			
R 09	Gleyic – low potential	Unacceptable	Duplex soil – Surface zone problem
R 14	Gleyic – low potential	Unacceptable	Duplex soil – Surface zone problem
R 22	Gleyic – low potential	Unacceptable	Duplex soil – Surface zone problem
Class E			
R 23	Arable	Poor	Water ponding and waterlogged soil expected
R 15	Grazing	Poor	Water ponding and waterlogged soil expected
R 17	Arable	Poor	Water ponding and waterlogged soil expected
R 20	Arable	Poor	Water ponding and waterlogged soil expected

With the assistance of Premier Mapping Africa, a detailed contour map of the Rehabilitated Field was used to identify surface water flow pathways and areas which are highly susceptible to ponding. Sampling sites were situated within these areas which can present valuable information on the effect of ponded areas on growth. Blue lines in Figure 7.10 indicate water pathways and the blue polygons shows areas where the water will accumulate and possibly pond. Figure 7.10 also illustrates the monitoring points in the Rehabilitated Field, categorized into different irrigability classes.

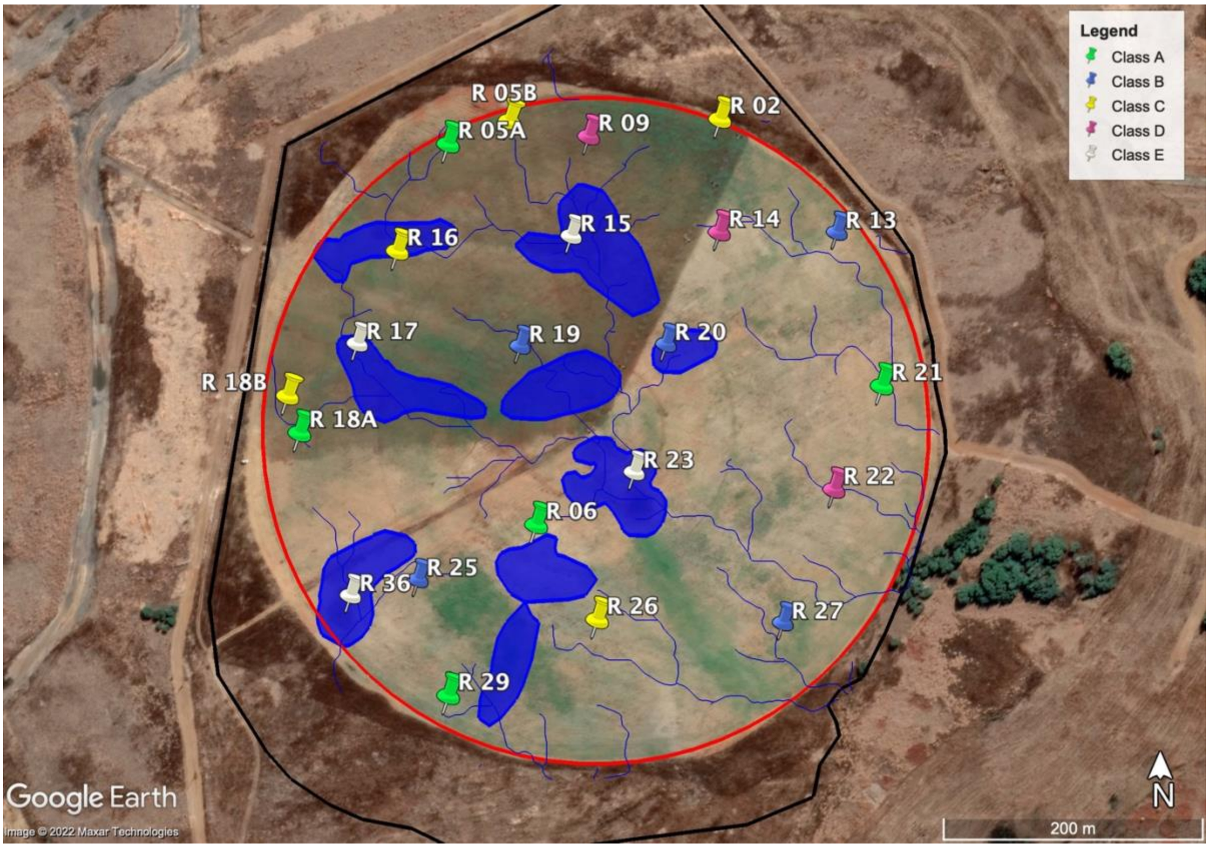


Figure 7.10: Google Earth image of the Rehabilitated Field indicating irrigability classes of monitoring points and concave areas potentially prone to ponding (Blue Polygons)

The blue polygons can also be referred to as depressions. Areas that showed no physical restrictions that were classified as arable according to the dryland classification, were deemed as suitable for irrigation if not situated in a depression.

The results from the sites presented in Table 7.4 and the proposed irrigability classification in Figure 7.10, are presented together in Table 7.5.

Table 7.5: Dry mass and LAI for the monitoring sites in different irrigability classes at the Rehabilitated Field

A (Good)			B (Moderate)			C (Good)			D (Unacceptable)			E (Poor)		
	t/ha	LAI		t/ha	LAI		t/ha	LAI		t/ha	LAI		t/ha	LAI
R 21	3,3	5,1	R 20	1,4	1,1	R 02	2,7	3,7	R 09	0,7	0,0	R 23	-	-
R 29	2,9	2,7	R 25	1,1	0,2	R 05B	3,1	4,2	R 14	0,9	0,2	R 15	-	-
R 05A	1,9	2,4	R 13	1,0	1,2	R 16	2,0	1,5	R 22	2,2	2,0	R 17	-	-

R 18A	1,1	0,6	R 19	1,6	1,1	R 18B	2,0	2,0	-	-	-	R 20	1,4	1,1
R 06	1,9	2,3	R 27	0,7	1,0	-	-	-	-	-	-	-	-	-
Ave	2,2	2,6		1,2	0,9		2,5	2,9		1,3	0,7		1,4	1,1
STDEV	0,9	1,6		0,4	0,4		0,5	1,3		0,8	1,1			

Class A had an average yield of 2.2 t/ha with a relatively good LAI of 2.6. Growth at these sites was as could be expected for areas suitable for dryland and irrigated production. Irrigation suitability and arable classification were similar for sites where there was no ponding or layers restricting infiltration, nor was there any severe “within profile” compaction present. R 18A was the exception, as a low yield and LAI was recorded at this sampling site. This low recorded yield may be the cause of low fertility or possible problems during the planting process as some areas were still rough even after soil preparation was done.

Class B represents sites which were classified as arable with the dryland classification system, but not suitable for irrigation with the proposed irrigability assessment criteria. The results show that yield and LAI was very low for these areas, and this corresponds with the irrigation suitability prediction. No outliers were recorded for class B within the five sampling sites. The poor growth is most likely due to the physical restrictions (layers and compaction) that were present in the profile. Only when these physical limitations are addressed through adequate ripping, may the suitability for irrigation improve. For class B, the physical restrictions proved to have a severe impact on pasture growth and yield.

Class C was classified as areas only having grazing suitability with the dryland classification system, but were deemed suitable for irrigation. Yield and LAI were the highest for class C, with an average of 2.5 t/ha and an average LAI of 2.9 m^2/m^2. Good infiltration and drainage were expected because of the greater amounts of coarse material present in the profile for these sites. This seemed to be the case and the reason for the superior growth in these areas. Most of the sampling classified as “grazing” showed more promising results than the areas classified as arable, indicating that soil depth is less important for storing water in the root zone under irrigated than dry land conditions. Figure 7.11 is from site R 05B (Class C) where good growth of the pasture is visible with a yield for the first harvest of 3.1 t/ha.

Figure 7.11: Site R 05B (Class C) with a yield of 3.1 t/ha recorded

Class D was classified as wetland areas with poor arable potential according to the dryland system. Unacceptable irrigation suitability was also predicted with the proposed Irrigability Assessment System. R09 and R14 recorded very poor growth and low yields as was expected. The G horizon (very high clay content) formed an almost impenetrable layer, limiting aeration and water infiltration, which resulted in poor establishment and growth. Such areas may improve over time with proper soil cultivation like ripping. Crop germination and establishment may also improve and ease the impact of irrigation and rainfall on the surface, allowing infiltration to take place. Figure 7.12 shows site R 09 (Class D) where only 0.7 t/ha was recorded. This indicates the high variability in the Rehabilitated Field, as the areas depicted in Figures 7.11 and 7.12, are situated less than 30 m from each other.

Figure 7.12: Poor growth at R 09.

Site R 22, Class D, produced high yields and good growth which was not expected. Cracks in the clay surface were observed, and different types of clay react differently to water. The cracks in the clay at R 22 are likely the result of the ability of the clay to swell and shrink. These cracks allow better water infiltration and aeration. This was not observed for sites R 09 and R 14, so it appears that R 22 had a different clay type. Figure 7.13 represents site R 22. Fescue dominated lucerne at this site because even though water infiltration and aeration were better than expected, it still remains difficult soil conditions for lucerne growth and establishment.

Figure 7.13: Fescue dominated lucerne growth at site R 22 (Class D) (December, 2022)

Class E represents sampling points in areas that are prone to ponding. Only site R 20 was accessible for sampling. The rest were constantly ponded and could not be sampled. Poor establishment and growth were observed in these areas. Topography analysis indicates several areas that are prone to ponding. R20, which is also a site allocated to class B, was the only ponded site that was accessible. A below average yield was recorded for R 20 of 1.4 t/ha. Even if a surface depression area exhibits high infiltrability, ponding is bound to occur in a high-rainfall area like Mpumalanga. It is recommended that unless depressions have extremely high infiltrabilities and high hydraulic conductivities in the profile to drain excess water, they should be classified as class E that is poorly suitable for irrigation.

Figure 7.14 presents normalised average yield and LAI for the various monitoring sites, arranged from lowest to highest LAI. This data was normalised to more easily compare trends between canopy cover and dry matter production. The graph indicates a correlation between yield and LAI.

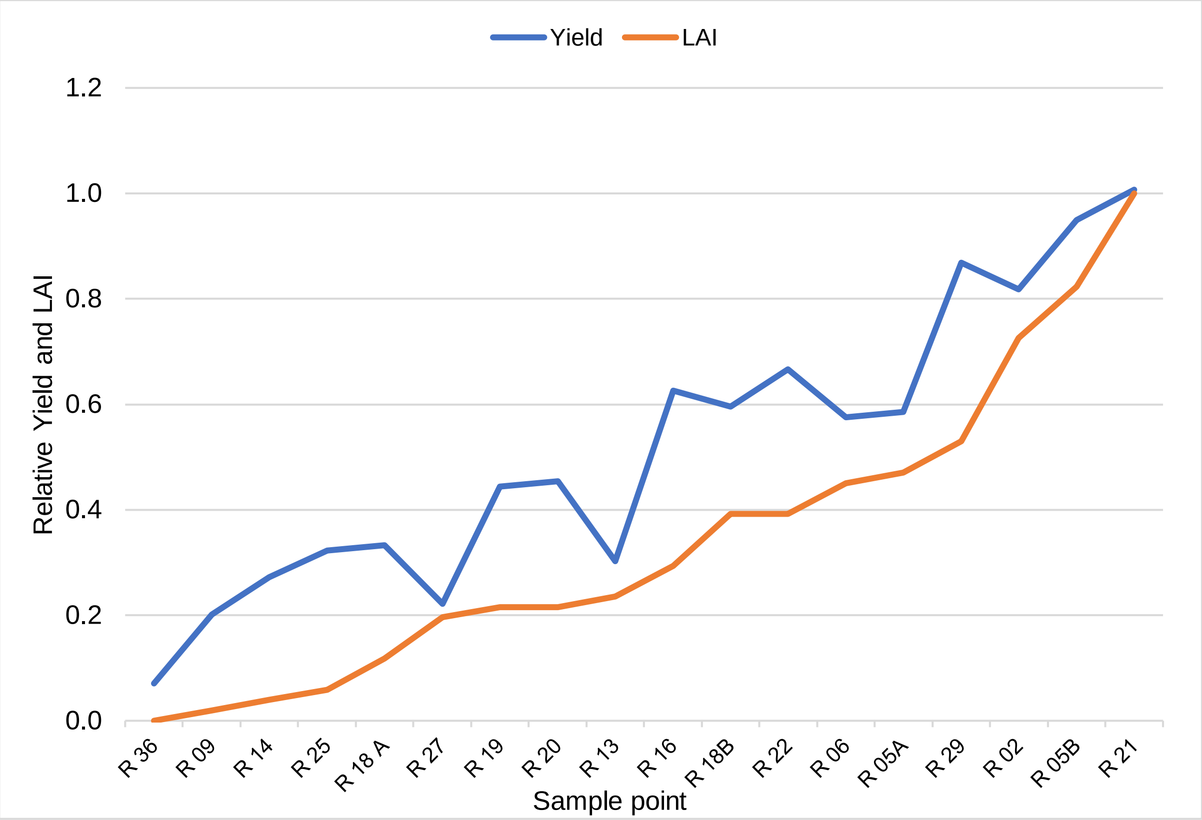


Figure 7.14: Normalised LAI and yields for the sampling points

A clear relation between LAI and yield can be seen in Figure 7.14. Fescue has a lower canopy cover than lucerne and it also likely has a lower yield.

Figure 7.15 represents the yields at the Rehabilitated Field from the highest to the lowest. The green bars indicate the areas that were classified with a good irrigability, the blue bars indicate areas that were classified as moderately suitable for irrigation and the grey bars as poorly suitable for irrigation. The orange bars represent the areas that were classified as unacceptable for irrigation. Although it was not possible to access these areas to take actual measurements, the production on them was visibly far below the lowest yield measured (R09 – 0.7 t/ha) and for this reason were arbitrarily assigned an uneconomical yield of only 0.25 t/ha to give a more complete picture of the relationship between irrigability classification and productivity.

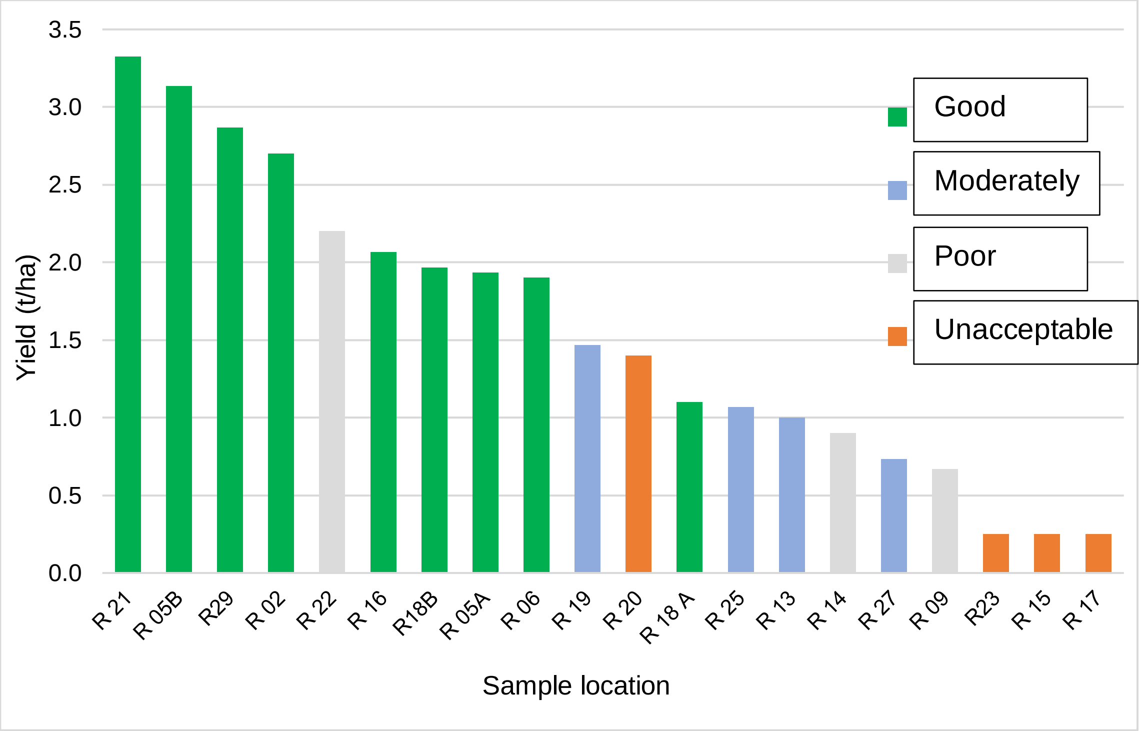


Figure 7.15: Yields at locations in the Rehabilitated Field ranked from highest to lowest

As explained before, R22 consisted of a different type of clay which may be the reason for the unexpected result. As for R20, in the map shown in Figure 7.10, it is visible that R20 was situated on the border of an area where ponding was expected, this area was ponded, but not to the extent where R20 was permanently wet and submerged under water. This is the reason for the higher yield than expected. If not for the ponding area, R20 would have been classified as moderately suitable for irrigation.

If R20 and R22 were to be excluded from the graph, it would show that when the yields are sorted from highest to lowest, it would fit the classification system according to areas that are suitable, moderately suitable, poorly suitable and unacceptable for irrigation. This data gives confidence in the assessment system used to define irrigation suitability.

7.4 Conclusion

The irrigated Rehabilitated Field at Mafube is a very valuable site for research due to the high spatial variability present in terms of soil chemical and physical properties, as well as in topography. The Rehabilitated Field at Mafube consists of areas that are highly suitable for irrigation, as well as areas completely unacceptable for irrigation.

Areas with no physical limitations that were classified as arable with the standard dryland potential classification system, were also deemed suitable for irrigation with the proviso that these areas are not located in depressions.

Where compacted layers in the profile were identified with the penetrometer, the arable capability classification was significantly affected under irrigation, and low yields were recorded for these areas. If adequate ripping of the soil was done initially, the outcome of the pasture yield results may have been completely different regarding compaction and restricting layers present in the profile. Root studies at these sampling sites are recommended for future research to see if the reason for poor performance is as expected.

The areas that were classified as grazing due to a large fraction of coarse material in the profile, had the highest yields under irrigation. This may be because the coarse material in the profile increased the infiltrability, thereby creating a suitable profile for irrigation. Coarse material in the profile may result in a lower water storage potential in the soil, which is not ideal for dry land crop production, but of limited concern if high frequency irrigation can be applied. This appears to be an important distinguishing feature between arable and irrigable soil conditions. It is recommended for future studies to do multiple water infiltration rate tests with a dual-head infiltrometer. These tests may assist with identifying areas with surface zone problems such as the areas with a gleyic topsoil.

Depressions that may result in ponded areas are also important in determining the irrigability of rehabilitated land. Although such depressions can be problematic for dryland production too in wet seasons, it is expected that they are of greater concern under irrigation which will typically experience wetter conditions. It can be concluded from the pasture yield results that topography is an important factor in determining suitability for irrigation.

Topography and physical conditions appear to be key factors in determining the suitability for irrigation of rehabilitated land.

The topography in terms of the overall slope of an area is taken into consideration with the guidelines for rehabilitation of opencast coal mines, but when it comes to irrigation of a profile, a more detailed topographical analysis is required. This will assist in determining possible water flow pathways, areas that are prone to ponding and areas that have a high risk for runoff and erosion during heavy rain. Without this information, the dryland classification system cannot be used to determine the suitability for irrigation for rehabilitated land.

Considering the different factors that influenced the irrigability for the rehabilitated area, the standard dryland classification approach that served the mining industry well in the past, should probably not be used as is to assess irrigable potential of rehabilitated areas.

Chapter 8: Summary and Conclusions

Gypsiferous mine water utilized for irrigation has been shown to be an attractive alternative to mine water treatment. The possibility of irrigating rehabilitated land with mine water is a concept that is well worth pursuing, as off-site environmental impact is expected to be less than for irrigation of unmined land, and the large rehabilitated areas and their close proximity to mine water sources make them ideal sites to consider for irrigation.

The spatial variability of soil properties in the rehabilitated irrigated field at Mafube is much higher than for unmined areas. The high variability can be directly related to the rehabilitation processes. Both physical and chemical variability was high, but physical properties tend to be more difficult to ameliorate. The variability mentioned only refers to the Rehabilitated Field at Mafube, but this may not be the case for all other sites. Variability could probably be less if rehabilitation guidelines are meticulously followed, but this is not an easy task, so variability is likely to be an inherent property of rehabilitated mine lands. Whilst much spatial variation is not ideal for commercial crop production, it does present an ideal research site, where differences can be studied.

It can be concluded from the weed growth analysis in Chapter 5, that although there were good relationships between soil phosphate, organic carbon and growth, physical properties had a more significant effect on growth and yield than soil chemical properties did. The pasture mixture discussed in Chapter 7 also indicated a strong relationship between physical properties and dry mass harvested. The severe effect of compaction and restricting layers in the profile was seen in weed growth and the pasture mixture. If sufficient ripping of the rehabilitated land was done initially, this may not have been such a determining factor. The compaction and restricting layers present in the Rehabilitated Field are good examples of how soil properties can be affected if the guidelines are not meticulously followed. This signifies the importance of following the guidelines created for opencast coal mining as physical properties are very expensive to ameliorate after the rehabilitation process.

From the results of Chapters 6 and 7, it can be concluded that a dryland classification system does not include all of the factors necessary to determine the irrigability of rehabilitated land. Additional physical properties and topography need to be included to create a more accurate assessment of the suitability for irrigation and some of the measured parameters of the dryland system considered should be interpreted differently.

The final topography of rehabilitated land can be identified as arguably the most important factor for determining suitability for irrigation. Surface subsidence is mainly the reason for the change in topography post rehabilitation, and is difficult to predict, so a specific area's irrigability classification may change over time. Correct topographical reshaping will ameliorate the effect of surface subsidence and can even prevent it from occurring. This highlights the importance of reserving additional topsoil to fill any depression areas that may form. This advice is included in the 1980, 2007 and 2019 Rehabilitation Guidelines, so it should be an accepted practice in the mining industry. The results of not having reserved topsoil to fill depressions can be seen in some areas at the Mafube Rehabilitated Field. The effect of using the wrong soil type to fill depression areas are also visible and proved to create unsuitable conditions for crop production under dryland or irrigated conditions.

If the key issues regarding the irrigability of rehabilitated land are addressed to create more suitable areas for irrigation, then irrigating with suitable mine water on rehabilitated land could be an effective and economical method of utilizing mine water, thereby also increasing the area of rehabilitated land available for agriculture. This will be a breakthrough for both mining and agriculture, as thousands of hectares are potentially available for mine water irrigated agricultural production, that will save large amounts of money on alternative water treatment, produce crops and create jobs, with limited environmental impact. It is certainly worth investing effort into addressing any limitations to this practice.

References

ANNANDALE J.G., BELETSE, Y.G., STIRZAKER, R.J., BRISTOW, K.L. & AKEN, M.E. 2009. Is Irrigation with Coal-Mine Water Sustainable? International Mine Water Conference. Pretoria, South Africa. 19th – 23rd October 2009. 337 – 342.

ANNANDALE, J.G., BENADÉ, N., JOVANOVIC, N.Z., STEYN, J.M. & DU SAUTOY, N. 1999. Facilitating Irrigation Scheduling by Means of the Soil Water Balance Model. Water Research Commission Report No. 753/1/99, Pretoria, South Africa. 285 pp.

ANNANDALE, J.G., DU PLESSIS, H.M., TANNER, P.D. & BURGESS, J. 2018. Using a risk based, site-specific Decision Support System to determine the suitability of mine water for irrigation. Mine Water Conference. Pretoria, South Africa. 10-14 September.

ANNANDALE, J.G., JOVANOVIC, N.Z., HODGSON, F.D.I., USHER, B.H., AKEN, M.E., VAN DER WESTHUIZEN, A.M., BRISTOW, K.L. & STEYN, J.N. 2006. Prediction of the environmental impact and sustainability of large-scale irrigation with gypsiferous mine-water on groundwater resources. *Water SA*: 32: 21-28.

ANNANDALE, J.G., JOVANOVIC, N.Z., TANNER, P.D., BENADÉ, N. & DU PLESSIS, H.M. 2002. The Sustainability of Irrigation with Gypsiferous Mine Water and Implication for the Mining Industry in South Africa. *Mine Water and the Environment*: 21: 81-90.

ANNANDALE, J.G., JOVANOVIC, N.Z., PRETORIOUS, J.J., LORENTZ, S.A., RETHMAN, N.F. & TANNER, P.D. 2001. Gypsiferous mine water use in irrigation on rehabilitated open-cast mine land: Crop Production, soil water and salt balance. *Ecological Engineering:* 17: 153-164.

ANNANDALE, J.G., TANNER, P.D., DU PLESSIS, H.M., BURGESS, J., RONQUEST, Z.D. & HEUER, S. 2019. Irrigation with mine affected waters: A demonstration with untreated colliery water in South Africa. *Mine Water: Technological and Ecological Challenges:* 71-76.

BARKEMEYER, R., STINGER, L.C., HOLLINS, J.A. & JOSEPH, F. 2015. Corporate reporting on solutions to wicked problems: sustainable land management in the mining sector. *Environmental Science & Policy:* 48: 196-209.

BUREAU OF FOOD AND AGRICULTURAL POLICY. 2012. A report by BFAP: Evaluating the impact of coal mining on agriculture in the Delmas, Ogies and Leandra districts – with a specific focus on maize production.

BUREAU OF FOOD AND AGRICULTURAL POLICY. 2015. The balance of natural resources: Understanding the long-term impact of mining on food security in South Africa: 31-36.

CANBULAT, I., VAN DER MERWE, J.N., VAN ZYL, M., WILKINSON, A., DAEHNKE, A. & RYDER, J. 2020. The development of techniques to predict and manage the impact of surface subsidence. Coaltech Task 6.9.1.

DU PLESSIS, H.M. 1983. Using lime-treated acid mine water for irrigation. *Water Science Technology:* 15: 145-154.

DU PLESSIS, H., ANNANDALE, J., BENADÉ, N., VAN DER LAAN, M., JOOSTE, S., DU PREEZ, C., BARNARD, J., RODDA, N., DABROWSKI, J., GENTHE, B. & NELL, P. 2017. Risk Based, Site-Specific, Irrigation Water Qualities Guidelines: Volume 1. Description of Decision Support System. Water Research Commission. Report No.: TT 727/17.

FERRÉ, T.P., WARRICK, A.W. 2005. Infiltration. *Encyclopaedia of Soils in the Environment:* 254-250.

GOOSEN, J. 2015. Topsoil Stripping and Management for Mine Rehabilitation. DOI: 10.13140/RG.2.1.2432.0484.

GREWAR T. 2019. South Africa’s options for mine-impacted water re-use: A review: *The Journal of the Southern African Institute of Mining and Metallurgy:* 119: 321-331.

HANCOX, P.J. 2016. The coalfields of South-Central Africa: *Episodes 3*: 2: 407-428.

JOVANOVIC, N.C., ANNANDALE, J.G., CLAASSENS, A.S., LORENTZ, S.A., TANNER, P.D., AKEN, M.E. & HODGSON, F.D.I. 2002. Commercial production of crops irrigated with gypsiferous mine water. *Water SA*: 28: 413 – 422.

JOVANOVIC, N.Z., BARNARD, R.O., RETHMAN, N.F.G. & ANNANDALE, J.G. 1998. Crops can be irrigated with lime-treated acid mine drainage. *Water SA*: 24: 113 – 122.

KOC, A., GOKKUS, A., TAN, M., COMAKLI, B. & SERIN, Y. 2004. Performance of tall fescue and Lucerne-tall fescue mixtures in highlands of Turkey. *New Zealand Journal of Agricultural Research:* 47: 61-65.

LE ROUX, S.G., DU PLESSIS, A. & CLARKE, C.E. 2019. MicroCT-based bulk density measurement method for soils. *Journal of the South African Institution of Civil Engineering:* 6: 2-9.

LIMPITLAW, D., AKEN, M.E., KILANI, J., MENTIS, M., NELL, J.P. & TANNER, P.D. 1997. Rehabilitation and soil characterization: Proceedings of the 11th International Conference on Coal Research, Calgary, 9-12 September, 1997. 297-309.

LIMPITLAW, D., AKEN, M.E., LODEWIJKS, H. & VILJOEN, J. 2005. Post-mining rehabilitation, land use and pollution at collieries in South Africa, Proceedings of the Colloquium: Sustainable Development in the Life of Coal Mining. South African Institute of Mining and Metallurgy, Boksburg, 13 July. 2005: 1-5.

LIMPITLAW, D. & BRIEL, A. 2014. Post-mining land use opportunities in developing countries – a review. *The Journal of the South African Institute of Mining and Metallurgy*: 114: 899 – 903.

LIMPITLAW, D. & MITCHELL, P. 2013. Mine closure – misplaced planning priorities. Mine Closure 2013: 3-14.

MENTIS, M.T. 1999. Diagnosis of the rehabilitation of opencast coal mines on the Highveld of South Africa. *South African Journal of Science:* 95: 210-215.

MINERALS COUNCIL OF SOUTH AFRICA. 2017: Integrated Annual Review 2017.

MUSHIA, N.M., RAMOELO, A. & KINGSLEY, K.A. 2016. The Impact of the Quality of Coal Mine Stockpile Soils on Sustainable Vegetation Growth and Productivity. *Sustainability:* 8: 546-558.

PATERSON, D.G., MUSHIA, M.N. & MKULA, S.D. 2018. Effects of stockpiling on selected properties of opencast coal mine soils. *South African Journal of Plant and Soil*: 1-6.

PULLES, W., HOWIE, D., OTTO, D. & EASTON, J. 1995. A Manual on Mine Water Treatment and Management in South Africa. Water Research Commission Report no. TT 80/96. Pretoria. South Africa.

SIMPSON, G.B., BADENHORST, L., JEWITT, G.P.W., BERCHNER, M. & DAVIES, E. 2019. Competition for land: The Water-Energy-Food Nexus and Coal Mining in Mpumalanga Province, South Africa. *Frontiers in Environmental Science:* 7:86.

SMETHURST, C.F., GARNETT, T. & SHABALA, S. 2005. Nutritional and chlorophyll fluorescence responses of lucerne (*Medicago sative*) to waterlogging and subsequent recovery. *Plant and Soil:* 270: 31 – 45.

TENNANT, D., SCHOLZ, G., DIXON, J. & PURDIE, B. 1992. Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture:* 32: 827-843.

THOMPSON, R. 2008. Waterponding: Reclamation technique for scaled duplex soils in western New South Wales rangelands. *Ecological Management & Restoration: 9*: 170-181.

VERMEULEN, P.D. & USHER, B.H. 2009. Operation and monitoring guidelines and the development of a screening tool for irrigation with coal mine water in Mpumalanga Province, South Africa. *Water SA:* 35: 379-386.

VERMEULEN, P.D., USHER, B.H. & VAN TONDER, G.J. 2008. Determination of the Impact of Coal Mine Water Irrigation on Groundwater Resources. *Water Research Commission report* No. 1507/1/08.

VRIENS, B., SKIERSZKAN, E., ST-ARNUALT, M., SALZSAULER, K., ARANDA, C., MAYER, K. & BECKLE, R. 2019. Mobilization of Metal(oid) Oxyanions through Circumneutral Mine Waste Rock Drainage. *ACS Omega*: 4: 10205-10215.

WANG, J., WANG, P., QIN, Q. & WANG, H. 2017. The effects of land subsidence and rehabilitation on soil hydraulic properties in a mining area in the Loess Plateau of China. *Catena* 159: 51-59.

WATSON, I. & OLALDE, M. 2019. The state of mine closure in South Africa - what the numbers say. *Journal of the Southern African Institute of Mining and Metallurgy* 119: 639-645.

WEYER, V.D., TRUTER, W.F., LECHNER, A.M. & UNGER, C.J. 2017. Surface-strip coal mine land rehabilitation planning in South Africa and Australia: Maturity and opportunities for improvement. *Resources Policy 54*: 117-129.

Appendix A – Water fitness for Use (DSS)

Irrigation Water Fitness-for-Use (Tier 2)

Sample identification:	46: Mafube 2017-2022
Site description:	47: Mafube

Water Analysis

Major constituents (mg/L)

Calcium	309.0	Bicarbonate	239.1

Magnesium 139.0 Chloride 22.0 Sodium 75.0 Sulphate 1494.0

pH	8.0	Total Dissolved Solids (TDS)	2278.1
Electrical Conductivity (mS/m)	324.0	Suspended Solids (SS)	72.0
SAR (mol/L)^0.5	0.9	Charge balance error: -13.9%	TDS / EC: 7.03

Biological Constituents

E. coli (counts/100 mL)	
Chemical Oxygen Demand (mg/L)	

Pesticides (µg/L)

Atrazine	

Nutrients (mg/L)

Total inorganic nitrogen (N)	0.7
Total inorganic phosphorous (P)	0.8
Total inorganic potassium (K)	34.0

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	400	0	Lead		0
Arsenic		0	Lithium		0
Beryllium		0	Manganese	800	0
Boron		0	Mercury		0
Cadmium		0	Molybdenum		0
Chromium		0	Nickel		0
Cobalt		0	Selenium		0
Copper		0	Uranium		0
Fluoride	600	0	Vanadium		0
Iron	800	0	Zinc	300	0

Site Specific Characteristics

Crop

1st Crop	Lucerne (Alfalfa)
Plant date (DD/MM)	1/4
2nd Crop	Fescue, tall
Plant date (DD/MM)	1/4

Irrigation management

Irrigation system	Overhead
Irrigation timing	Interval (days) 5
Refill option	Field capacity

Soil

Soil texture	Sandy loam
Soil depth (m)	1.2
Initial water content	Wet (FC)
Profile available water (mm)	144
Plant available water (mm/m)	120
Field capacity (m/m)	0.22
Wilting point (m/m)	0.10
Bulk density (Mg/m3)	1.40

Weather station	BELFAST (45 years)	MAP (mm)	799

Water Balance

Water balance components	Lucerne (Alfalfa)	Fallow	Fescue, tall
Mean seasonal irrigation (mm)	826	0	0
Mean seasonal rainfall (mm)	792	7	0
Mean seasonal evaporation (mm)	488	8	0
Mean seasonal transpiration (mm)	766	0	0
Mean seasonal evapotranspiration (mm)	1253	8	0
Mean seasonal drainage (mm)	360	3	0
Effective seasonal leaching fraction (%)	22.3	43.4	0.0
Total runoff (mm)	0.0	0.0	0.0
Effective annual leaching fraction (%)	22.4		

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Tier 2: Fitness-for-Use

Soil Quality of a Sandy loam soil with 825 mm irrigation p.a.

Soil profile salinity	Fitness-for-use	ECe (mS/m)	% of time soil profile salinity is predicted to fall within a particular Fitness-for-use category	
	Ideal	0 - 200	93	
	Acceptable	200 - 400	7	
	Tolerable	400 - 800		
	Unacceptable	> 800		
Soil Permeability	Fitness-for-use	Degree of reduced Permeability	% of time soil permeability is predicted to fall within a particular Fitness-for-use category	
			Surface Infiltrability	Soil Hydraulic Conductivity
	Ideal	None	91	97
	Acceptable	Slight	9	1
	Tolerable	Moderate		1
	Unacceptable	Severe		1
Oxidisable Carbon Loading	Fitness-for-use	COD Load (kg/ha per month)	% of time Chemical Oxygen Demand (COD) Load is predicted to fall within a particular Fitness-for-use category	
	Ideal	0 - 400	No data	
	Acceptable	400 - 1000		
	Tolerable	1000 - 1600		

	Unacceptable	>1600				
Trace Element Accumulation	Fitness-for-use		Number of years of 825 mm irrigation before Trace Elements reach accumulation threshold in topsoil			
	Ideal		> 200 years to reach soil accumulation threshold			
	Acceptable		150 to 200 years to reach soil accumulation threshold			
	Tolerable		100 to 150 years to reach soil accumulation threshold			
	Unacceptable		< 100 years to reach soil accumulation threshold			
	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold
	Al	2500	> 1000	Li	1250	No data
	As	50	No data	Mn	100	30
	Be	50	No data	Hg	1	No data
	Cd	5	No data	Mo	5	No data
	Cr	50	No data	Ni	100	No data
	Co	25	No data	Se	10	No data
	Cu	100	No data	U	5	No data
	F	1000	404	V	50	No data
	Fe	2500	758	Zn	500	404
	Pb	100	No data			

Yield and Quality of a Lucerne (Alfalfa) crop with 826 mm irrigation per season

Root Zone Effects	Fitness-for-use	Relative crop yield (%)	% of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
	Ideal	90 - 100	100	No data	100	100
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				
Leaf scorching when wetted	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:			
			Chloride (Cl)		Sodium (Na)	
	Ideal	None	None		None	
	Acceptable	Slight				
	Tolerable	Moderate				

	Unacceptable	Severe						
Contribution to NPK removal	Fitness-for-use	Contribution to estimated N P K Removal by crop	Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
	Ideal	0 - 10%					No param	281
	Acceptable	10 - 30%	100	6				
	Tolerable	30 - 50%						
	Unacceptable	>50%			100	7		
Microbial Contamination	Fitness-for-use	Excess infections per 1000 persons p.a.	Predicted excess infections per 1000 people p.a.					
	Ideal	<1	No data					
	Acceptable	1 - 3						
	Tolerable	3 - 10						
	Unacceptable	>10						
Qualitative Atrazine Damage	Fitness-for-use	Atrazine load (Lucerne (Alfalfa), SaLm) (g/ha)	% of time Atrazine load is predicted to fal within particular fitness-for-use category					
	Ideal	<90	No data					
	Acceptable	90 - 130						
	Tolerable	130 - 180						
	Unacceptable	>180						

Yield and Quality of a Fescue, tall crop with 826 mm irrigation per season

			% of time yield is within relative crop yield category, as affected by:			
	Fitness-for-use	Relative crop yield (%)	Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 - 100		No data		
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

			Degree of leaf scorching under sprinkler irrigation caused by:	
	Fitness-for-use	Degree of leaf scorching	Chloride (Cl)	Sodium (Na)
Leaf scorching when wetted	Ideal	None	No scorching parameter	No scorching parameter
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

			Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
	Fitness-for-use	Contribution to estimated N P K Removal by crop	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
Contribution to NPK removal	Ideal	0 - 10%	No param	0	No param	0	No param	0
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%						

	Fitness-for-use	Excess infections per 1000 persons p.a.	Predicted excess infections per 1000 people p.a.
Microbial Contamination	Ideal	<1	No data
	Acceptable	1 - 3	
	Tolerable	3 - 10	
	Unacceptable	>10	

Qualitative Atrazine Damage	Fitness-for-use	Atrazine load (Fescue, tall, SaLm) (g/ha)	% of time Atrazine load is predicted to fall within particular fitness-for-use category

	Ideal	<90	No data
	Acceptable	90 - 130	
	Tolerable	130 - 180	
	Unacceptable	>180	

Irrigation Equipment

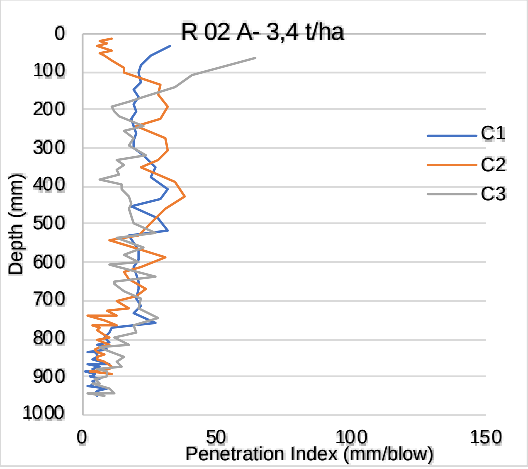
Corrosion or Scaling of Irrigation Equipment

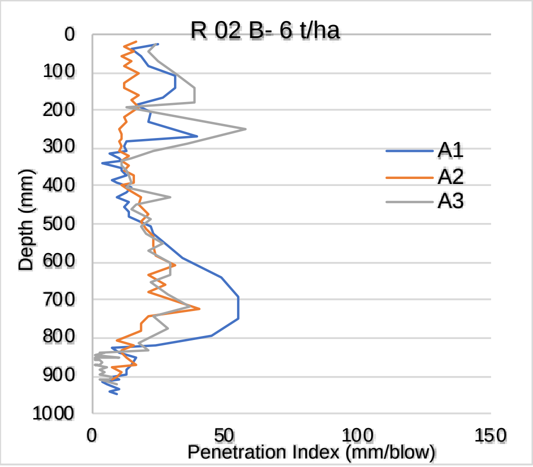
Fitness-for-use	Fitness for Use Category determined by the corrosion or scaling potential indicated by the Langelier Index			
	Corrosion (Langelier Index)		Scaling (Langelier Index)	
Ideal	0 to -0.5	Not Corrosive	0 to +0.5	
Acceptable	-0.5 to -1.0		+0.5 to +1.0	
Tolerable	-1.0 to -2.0		+1.0 to +2.0	1.16
Unacceptable	<-2.0		>+2.0	

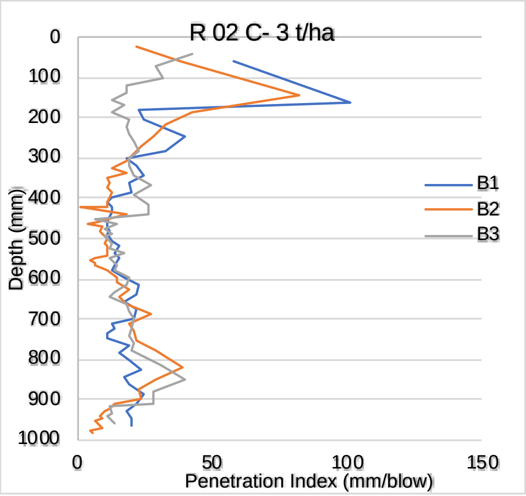
Clogging of Drippers

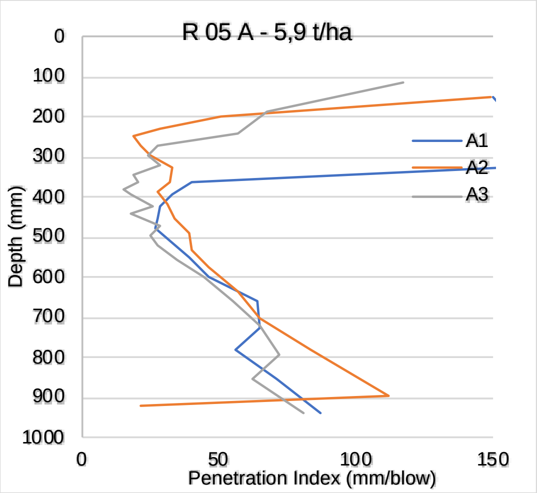
Fitness-for-use	Fitness for Use Category determined by the potential of an irrigation water constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		E.coli (10^6 per 100 mL)	
Ideal	<50		<7.0		<0.1		<0.2		<1	No data
Acceptable	50 - 75	72	7.0 - 7.5		0.1 - 0.5		0.2 - 0.5		1 - 2	
Tolerable	75 - 100		7.5 - 8.0		0.5 - 1.5	0.8	0.5 - 1.5	0.8	2 - 5	
Unacceptable	>100		>8.0	8.0	>1.5		>1.5		>5	

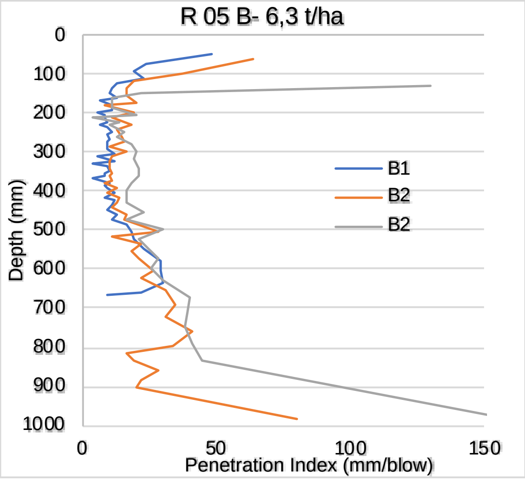
Appendix B – Penetrometer results from the Rehabilitated Field

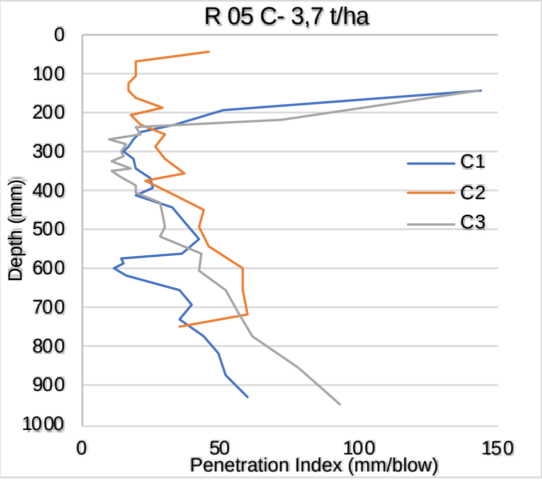


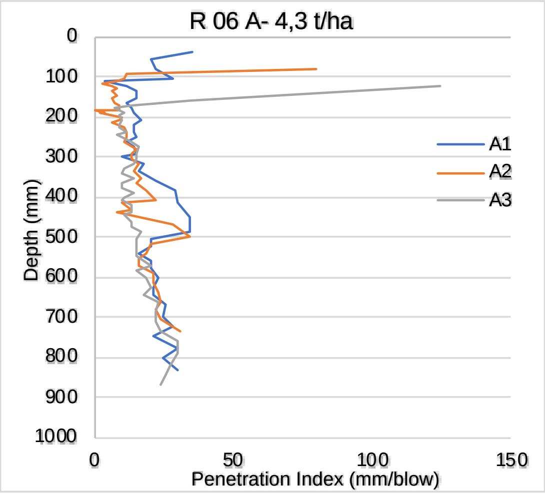








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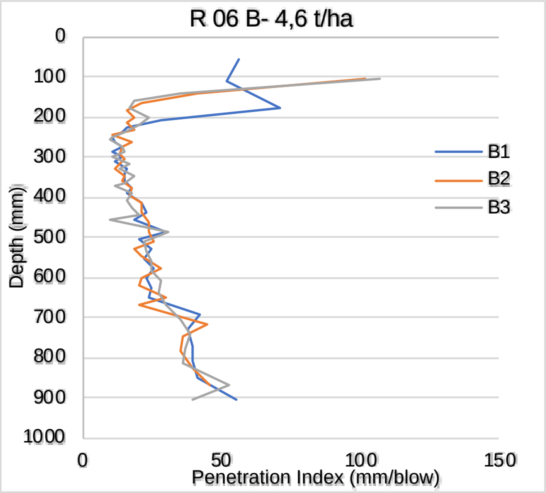
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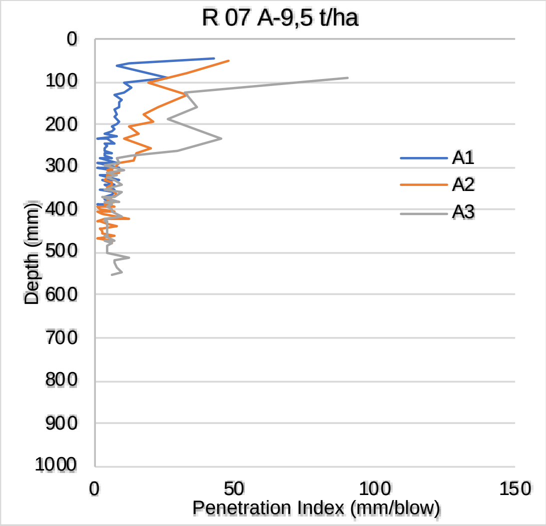
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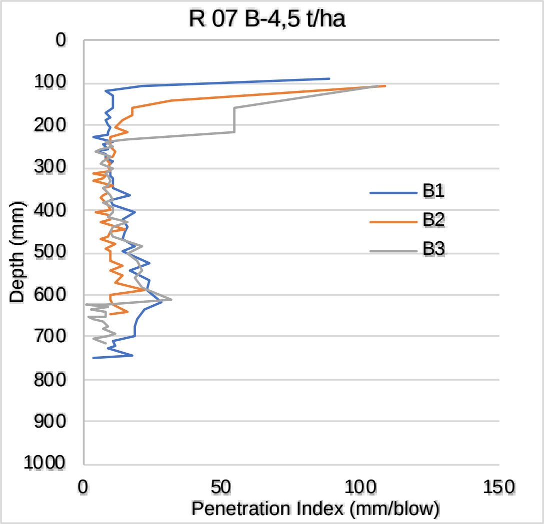
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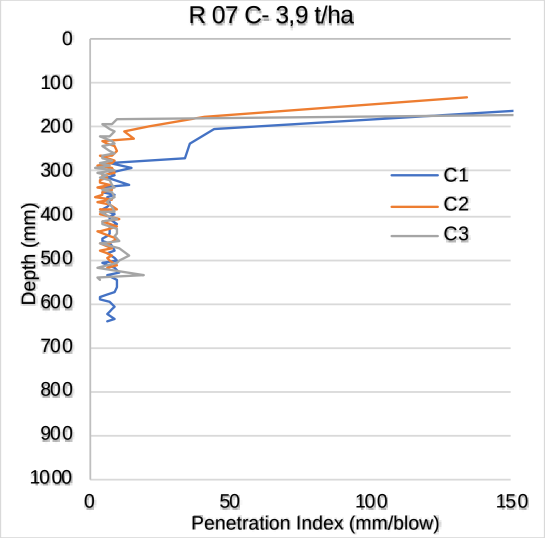
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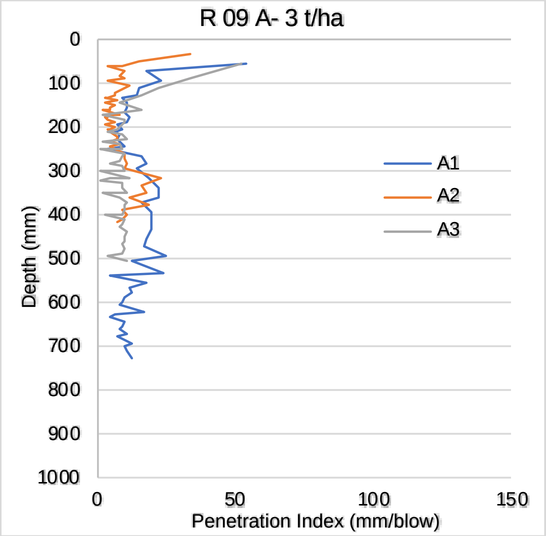
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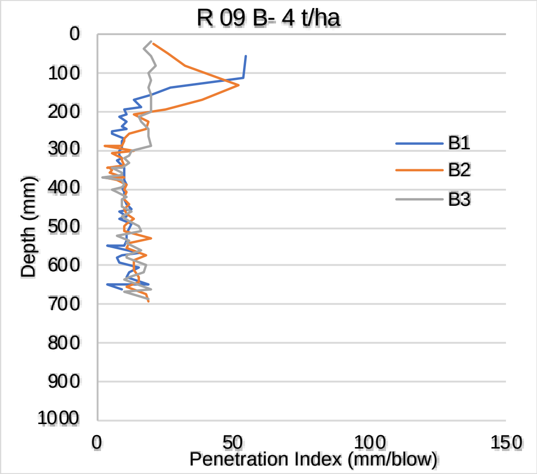
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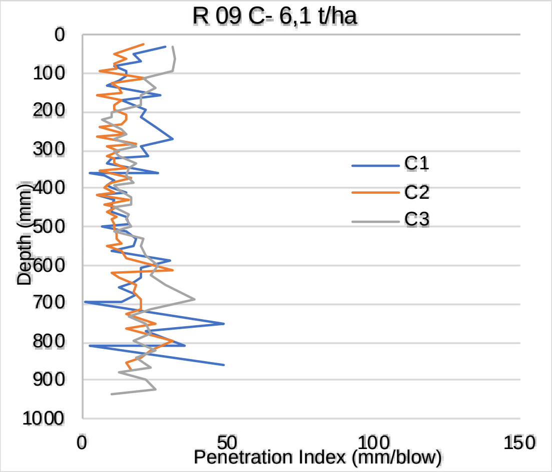
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3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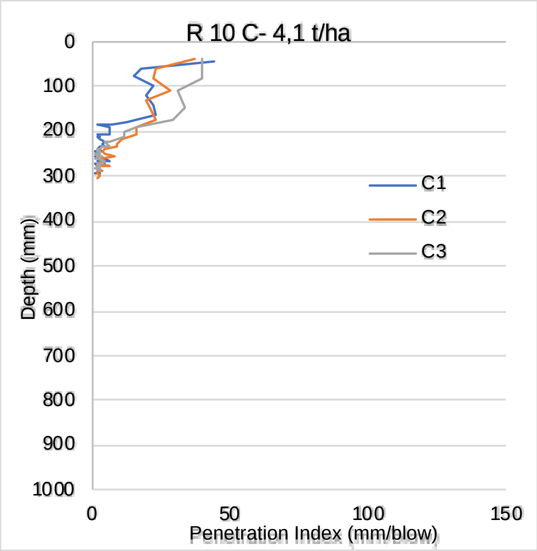
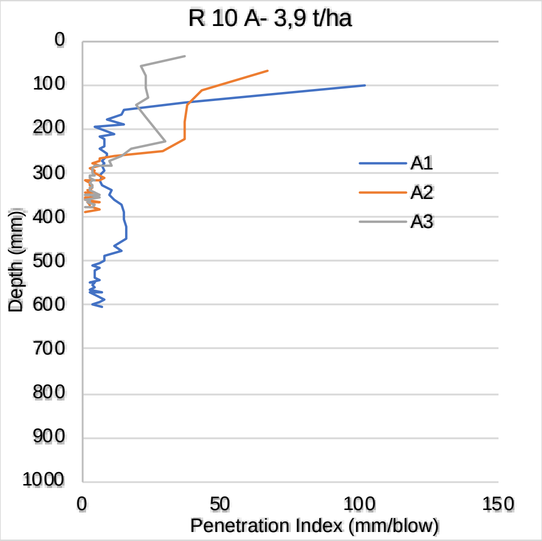
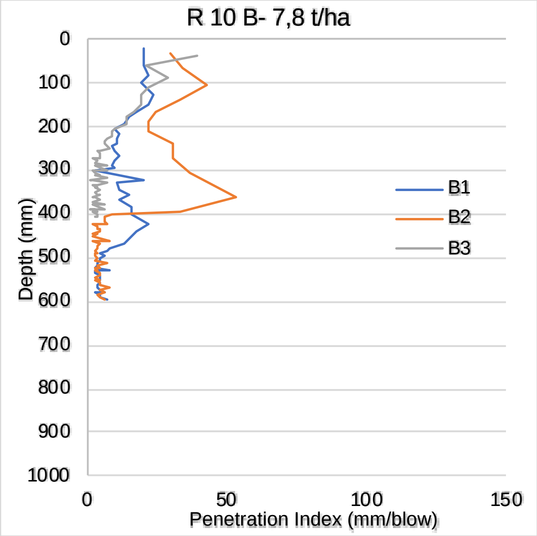
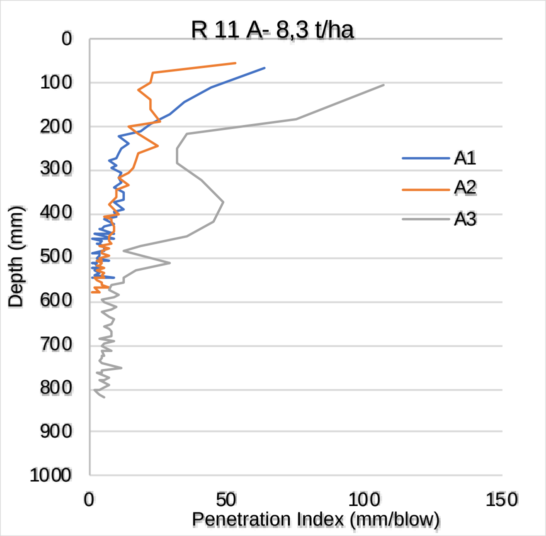
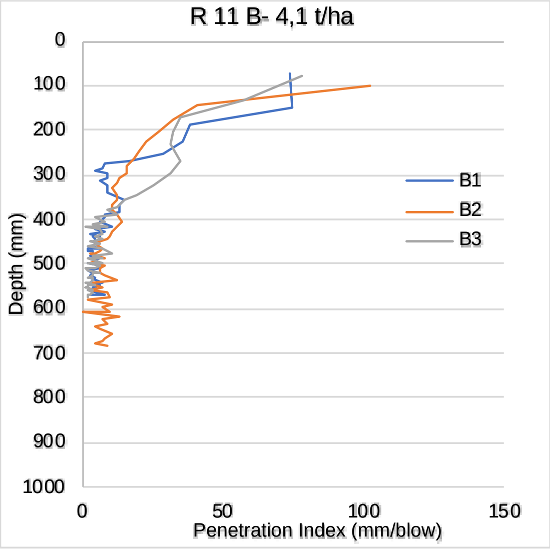
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

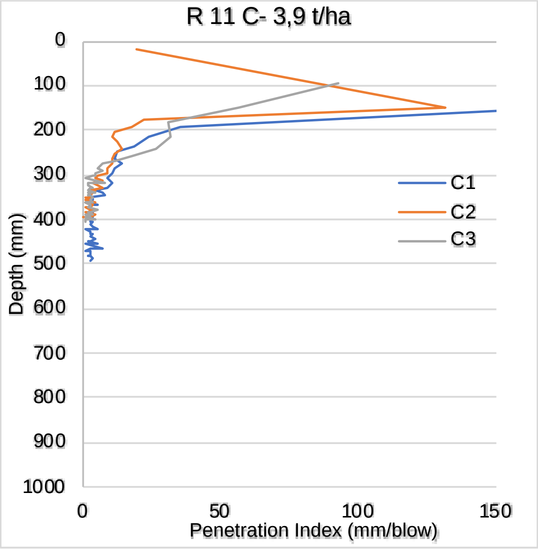

R 10 C- 4,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

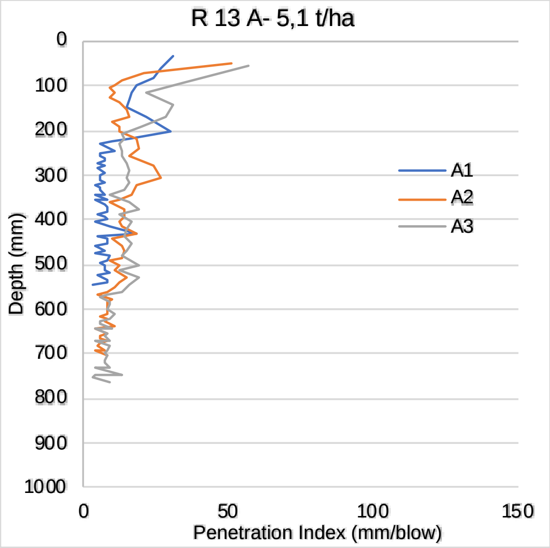

R 10 A- 3,9 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

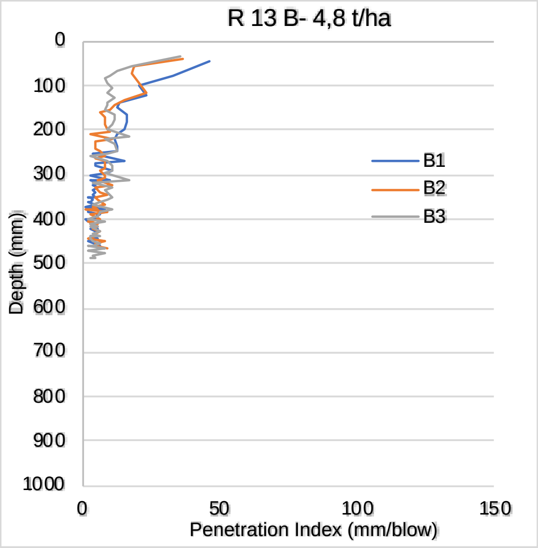

R 10 B- 7,8 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

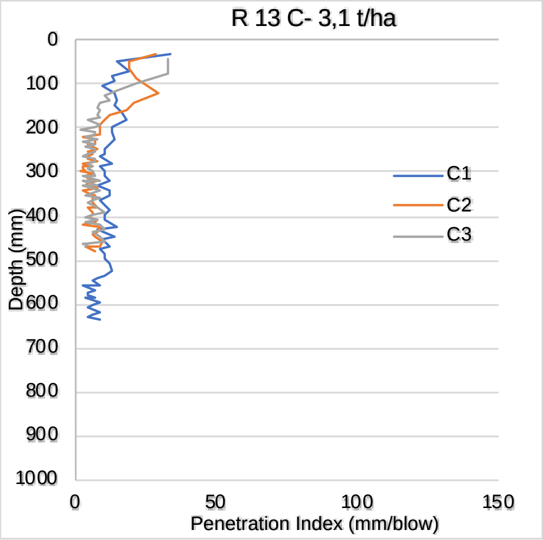

R 11 A- 8,3 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

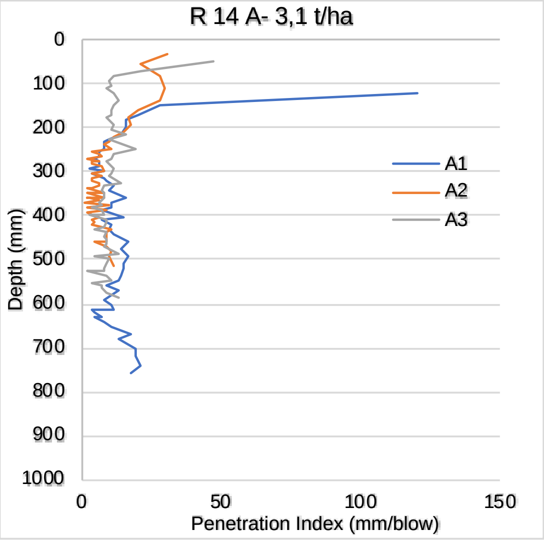

R 11 B- 4,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

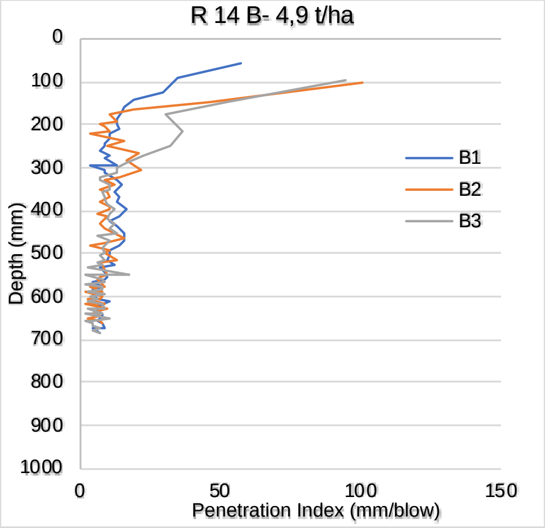

R 11 C- 3,9 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

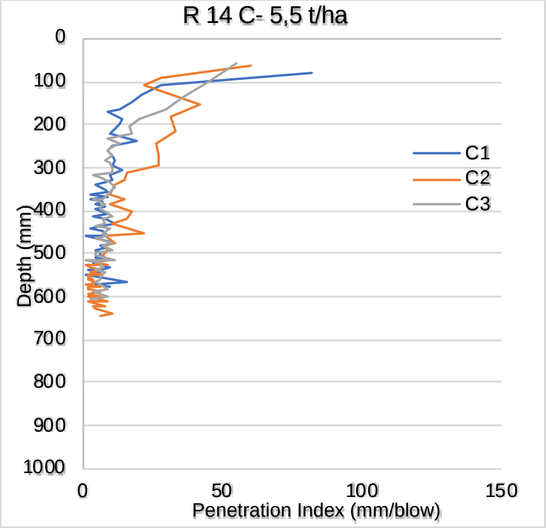

R 13 A- 5,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

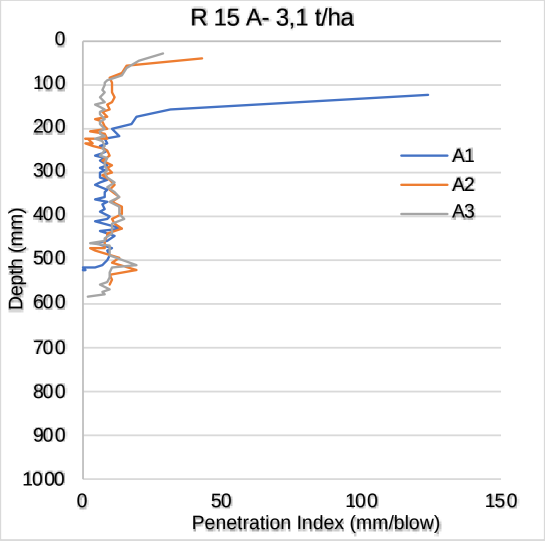

R 13 B- 4,8 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

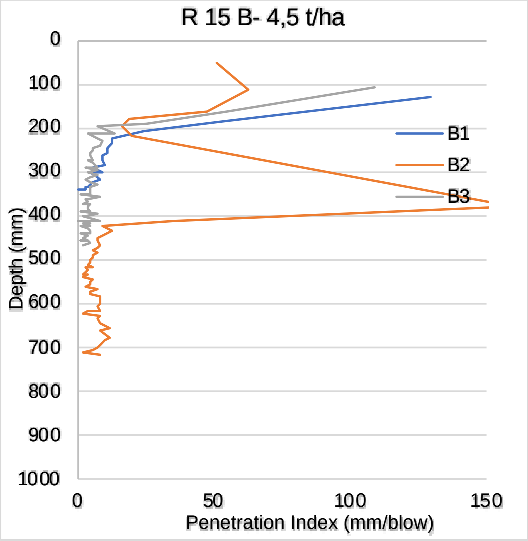

R 13 C- 3,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

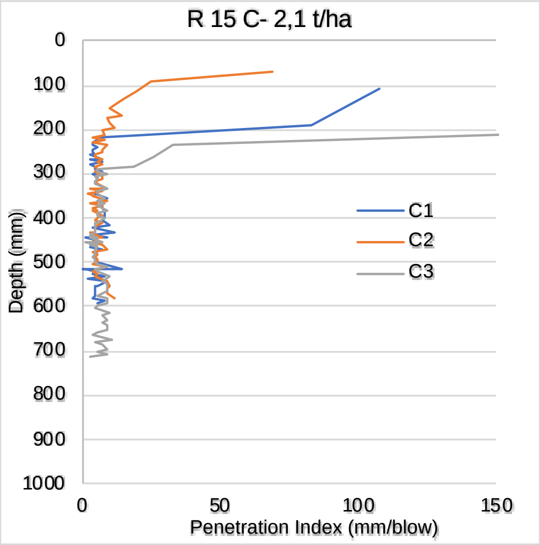

R 14 A- 3,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

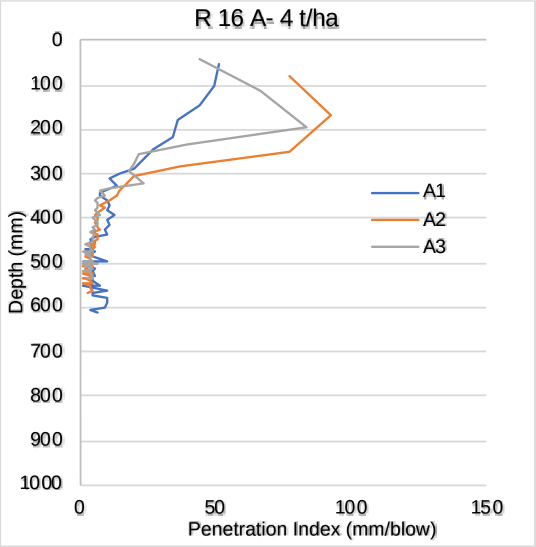

R 14 B- 4,9 t/ha

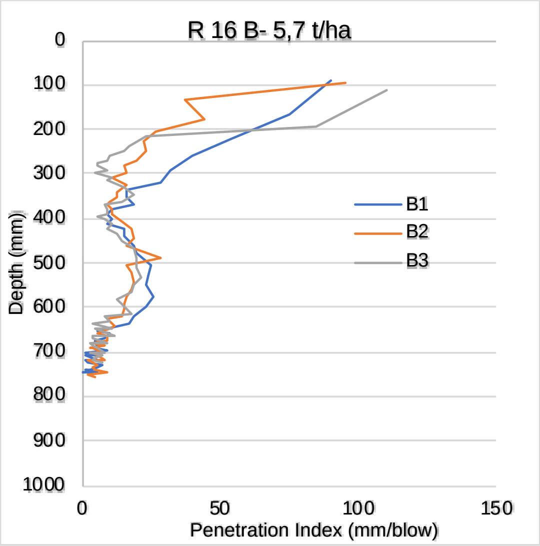

R 14 C- 5,5 t/ha

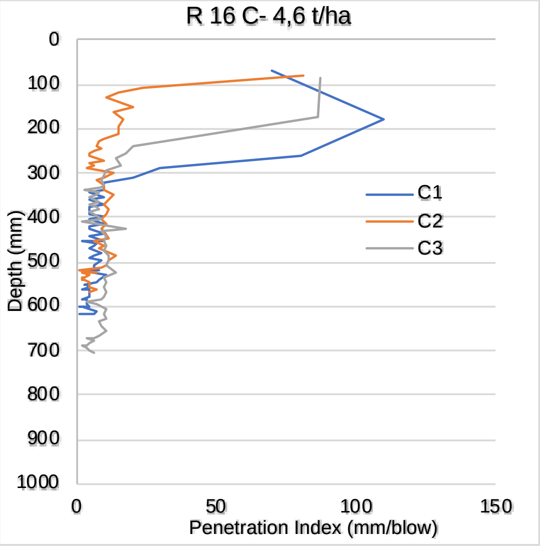

R 15 A- 3,1 t/ha

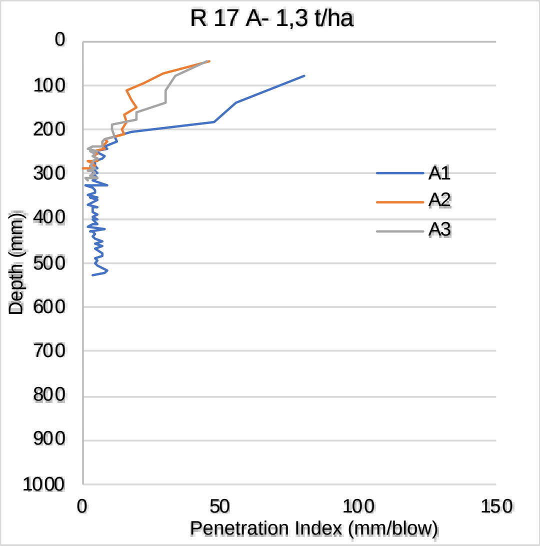

R 15 B- 4,5 t/ha

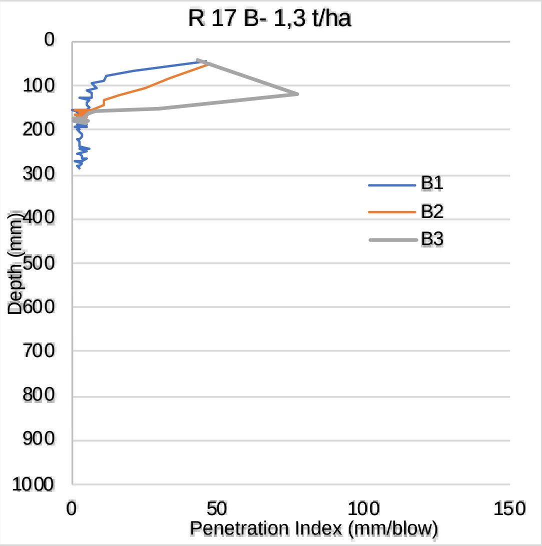

R 15 C- 2,1 t/ha

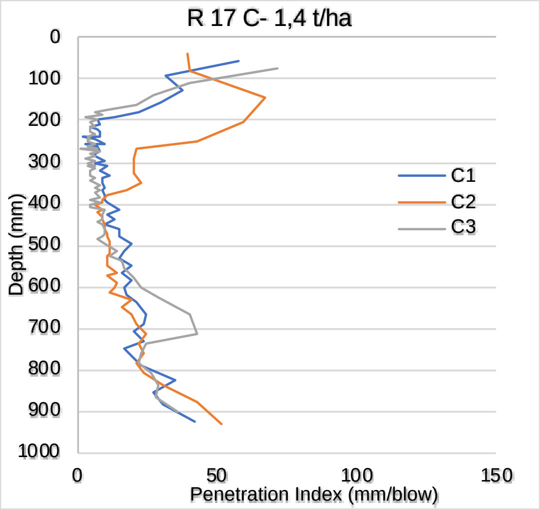

R 16 A- 4 t/ha

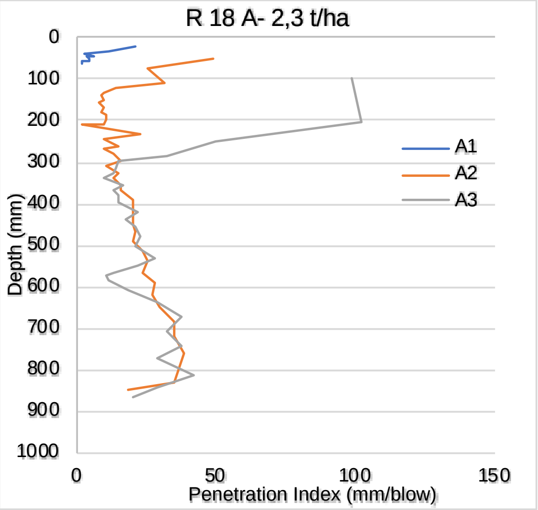

R 16 B- 5,7 t/ha

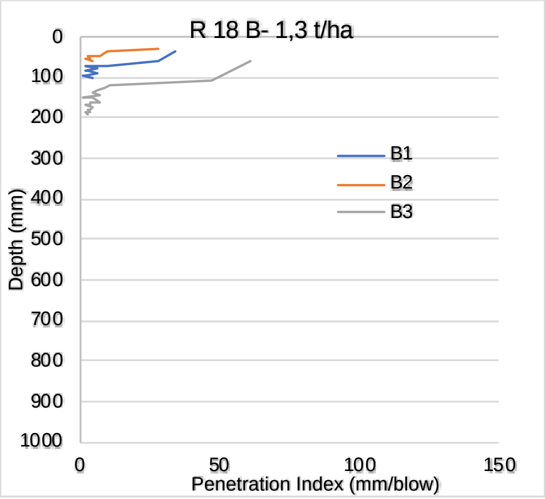

R 16 C- 4,6 t/ha

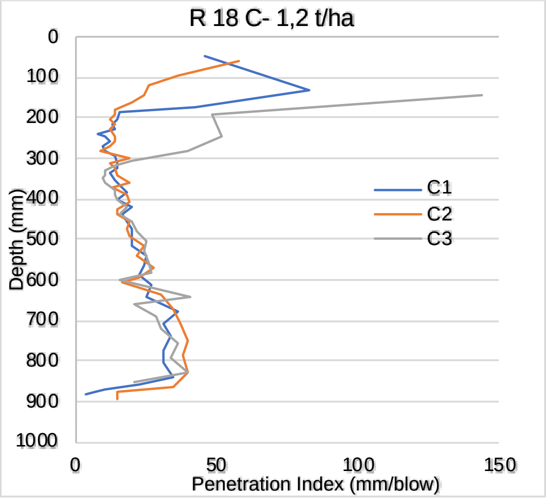

R 17 A- 1,3 t/ha

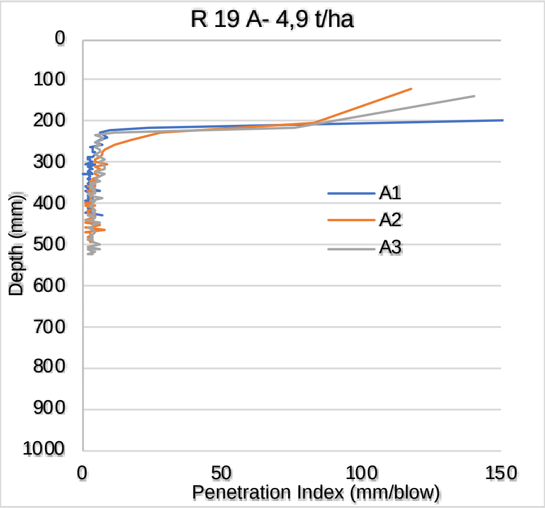

R 17 B- 1,3 t/ha

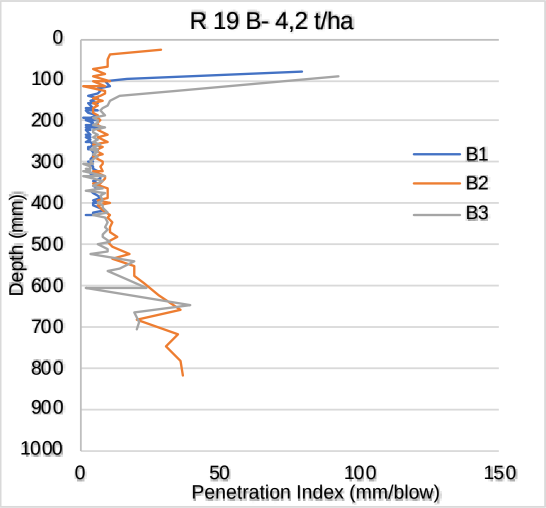

R 17 C- 1,4 t/ha

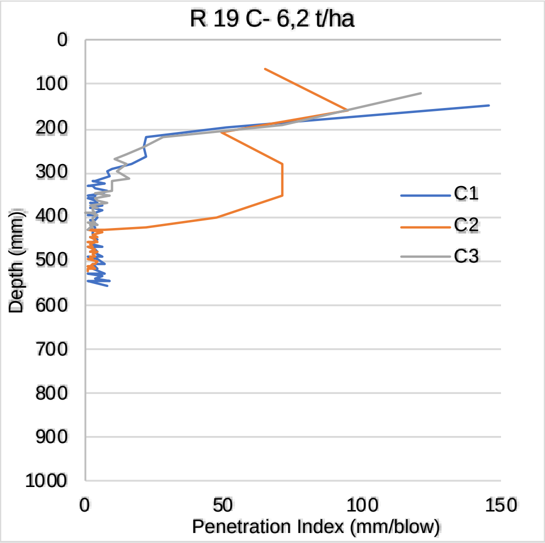

R 18 A- 2,3 t/ha

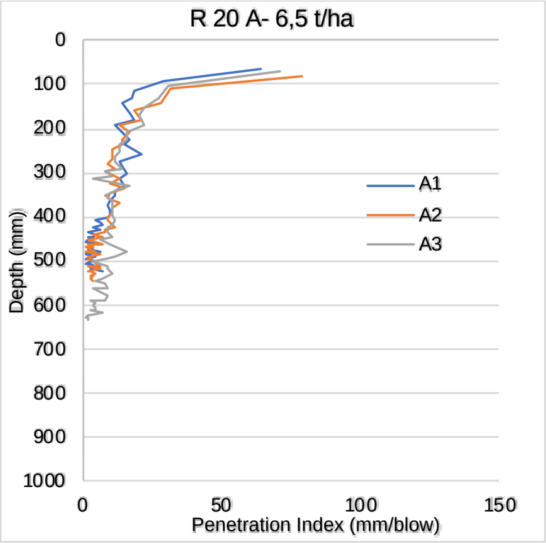

R 18 B- 1,3 t/ha

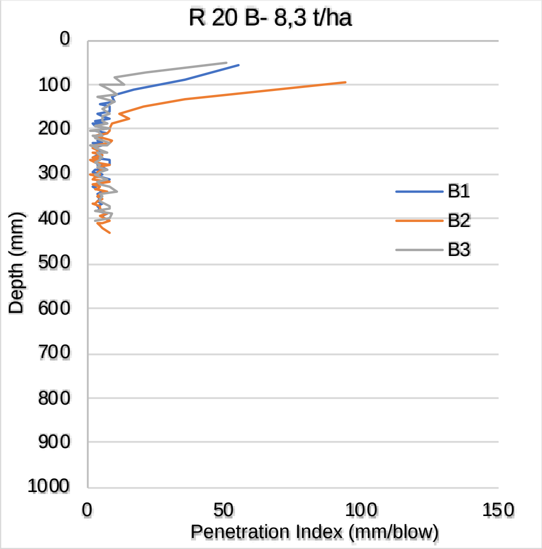

R 18 C- 1,2 t/ha

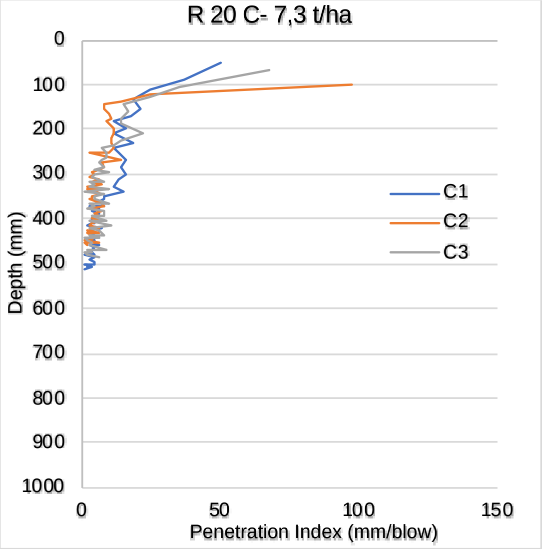

R 19 A- 4,9 t/ha

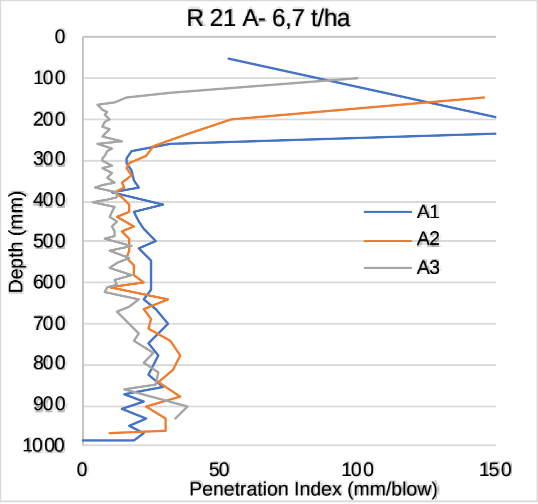

R 19 B- 4,2 t/ha

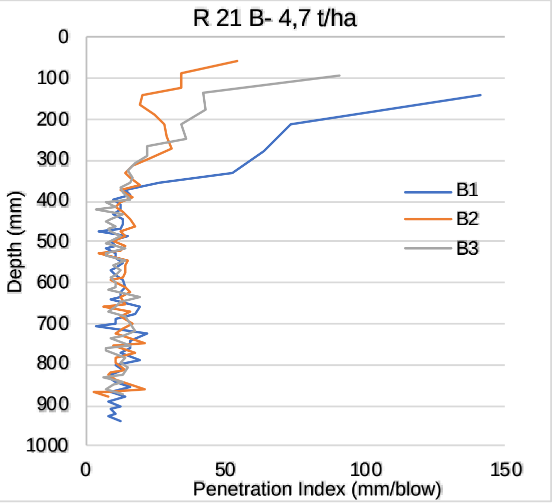

R 19 C- 6,2 t/ha

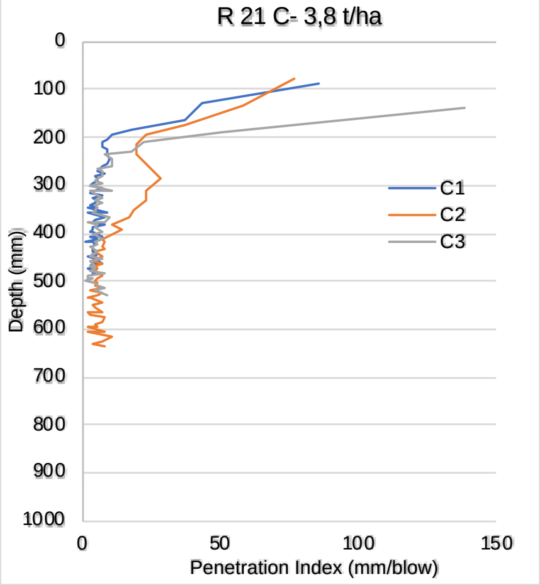

R 20 A- 6,5 t/ha

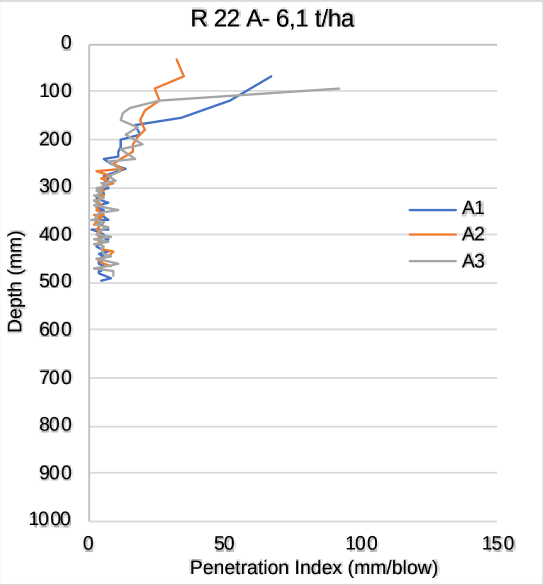

R 20 B- 8,3 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

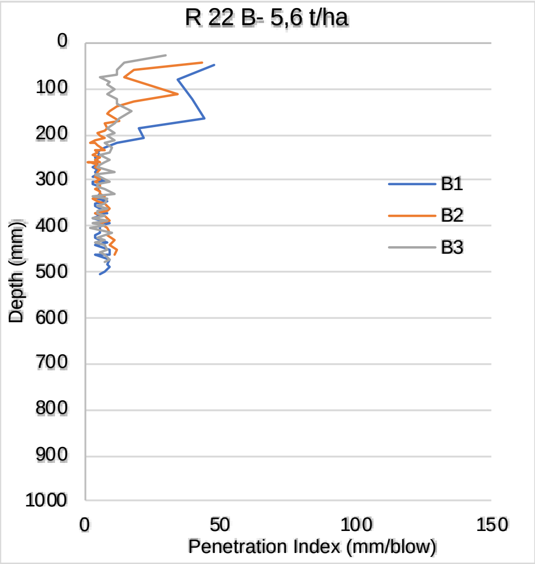

R 20 C- 7,3 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

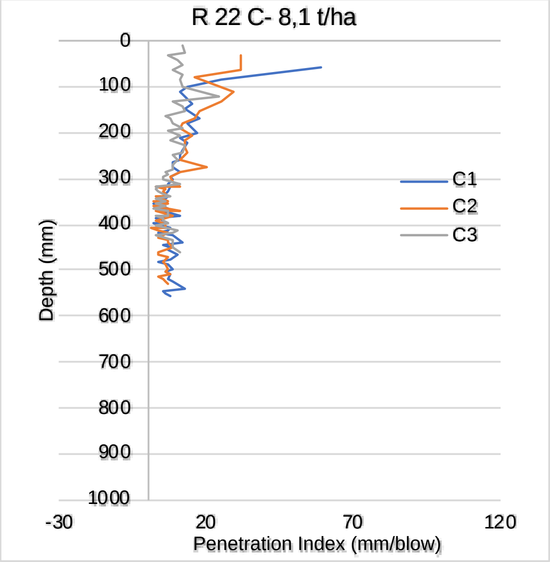

R 21 A- 6,7 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

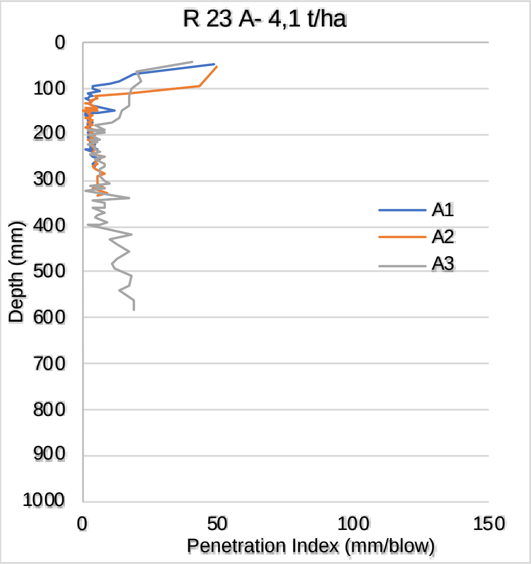

R 21 B- 4,7 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

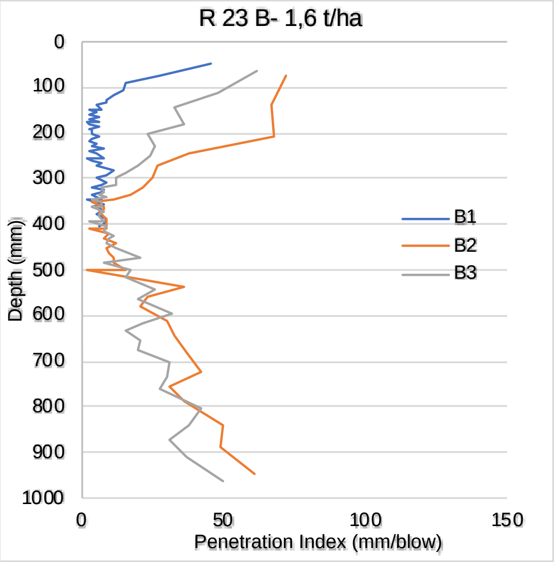

R 21 C- 3,8 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

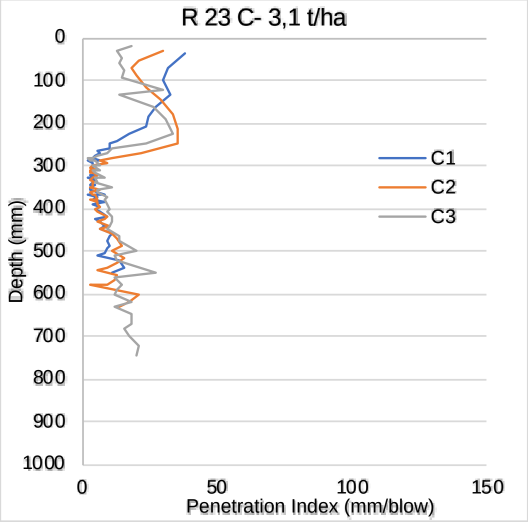

R 22 A- 6,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

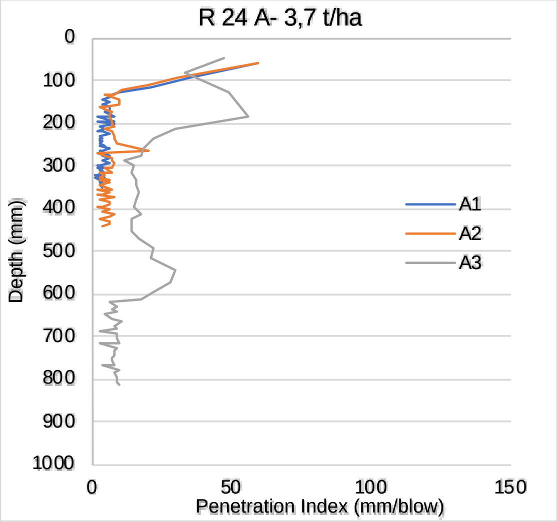

R 22 B- 5,6 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

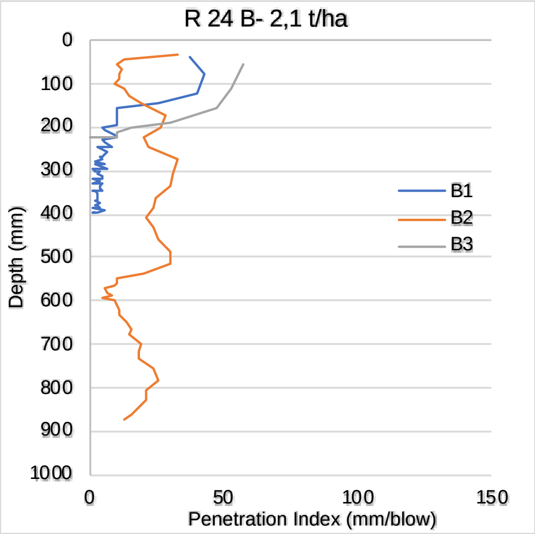

R 22 C- 8,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
-30
20
70
120
Penetration Index (mm/blow)
C1
C2
C3

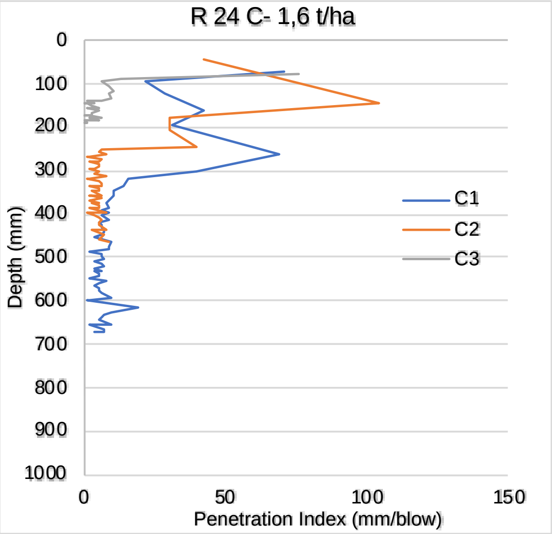

R 23 A- 4,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

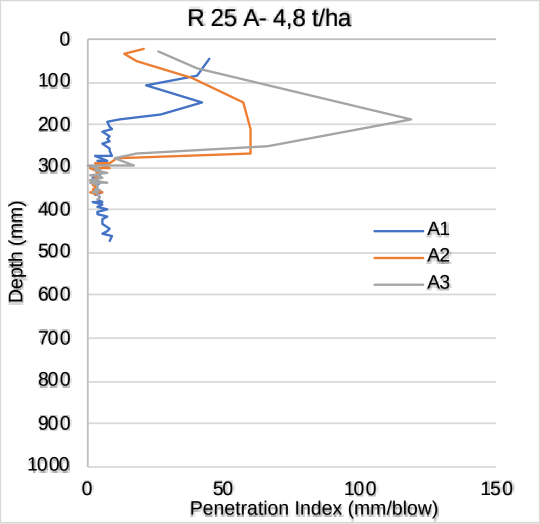

R 23 B- 1,6 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
B1
B2
B3

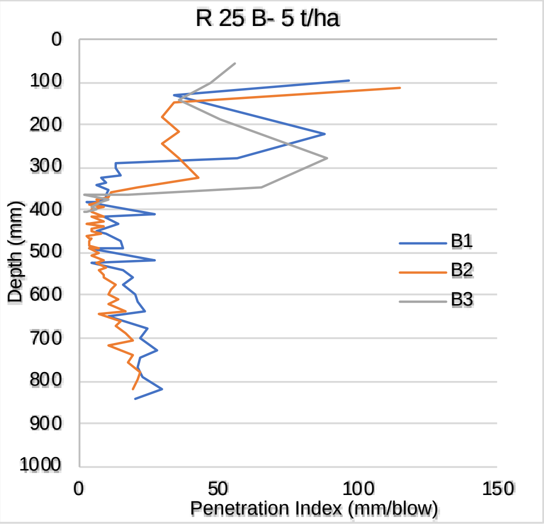

R 23 C- 3,1 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
C1
C2
C3

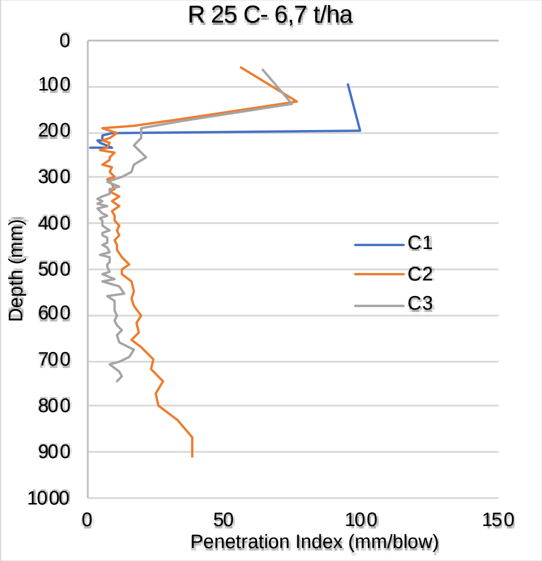

R 24 A- 3,7 t/ha
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
Penetration Index (mm/blow)
A1
A2
A3

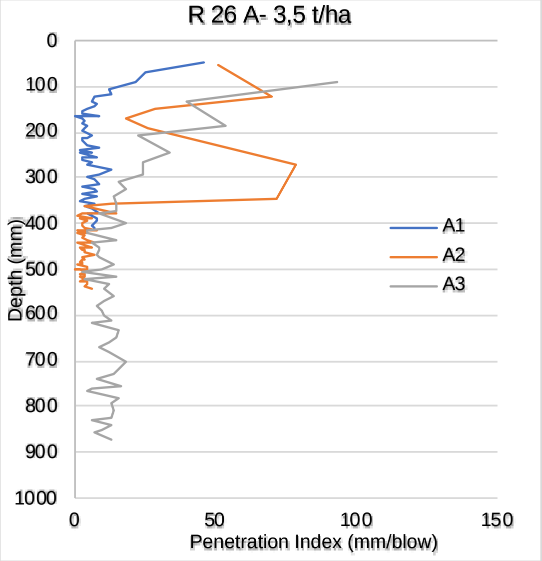

R 24 B- 2,1 t/ha

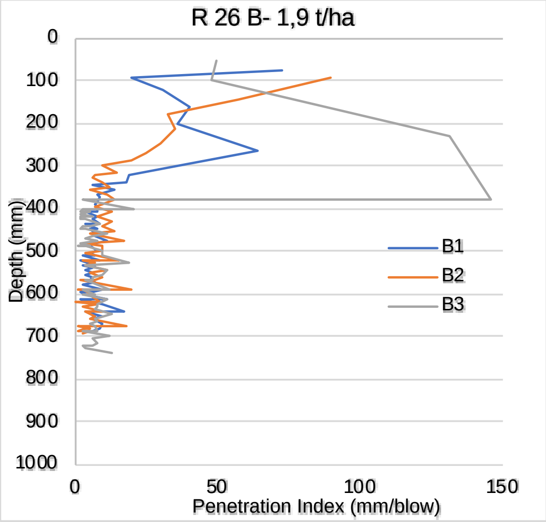

R 24 C- 1,6 t/ha

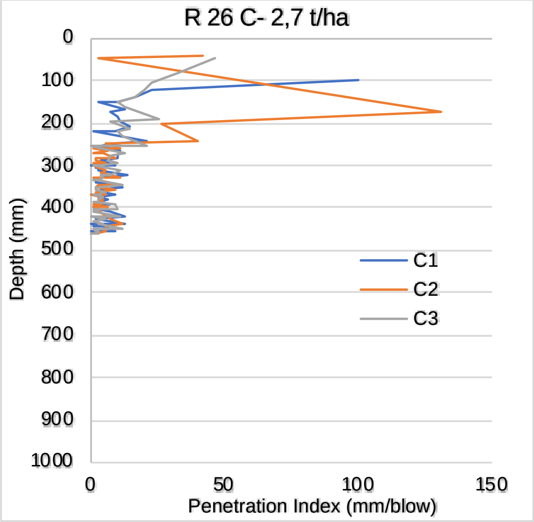

R 25 A- 4,8 t/ha

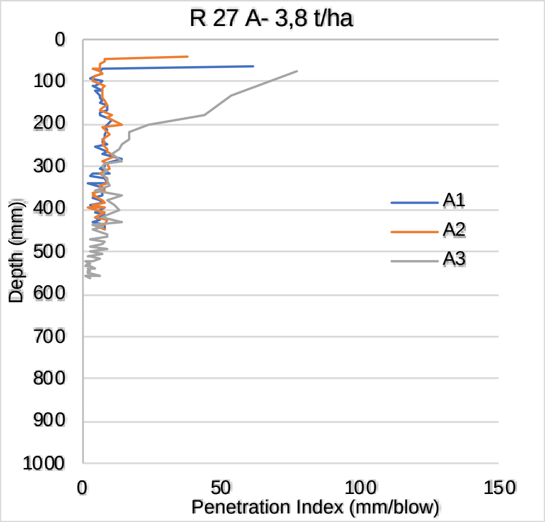

R 25 B- 5 t/ha

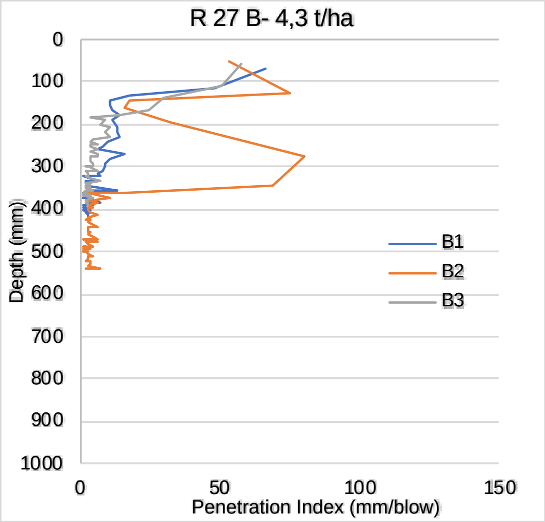

R 25 C- 6,7 t/ha

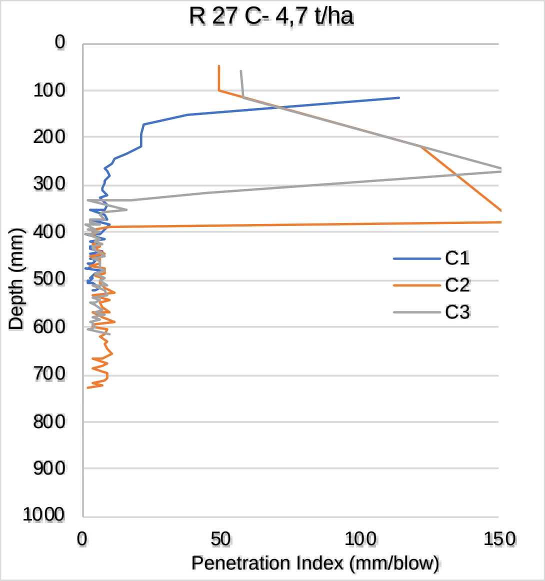

R 26 A- 3,5 t/ha

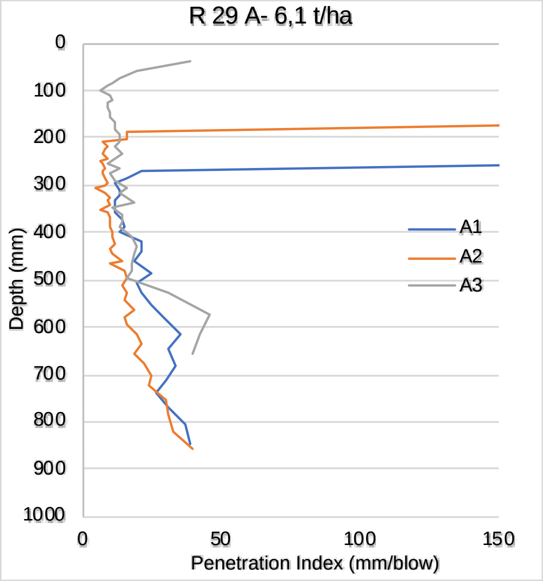

R 26 B- 1,9 t/ha

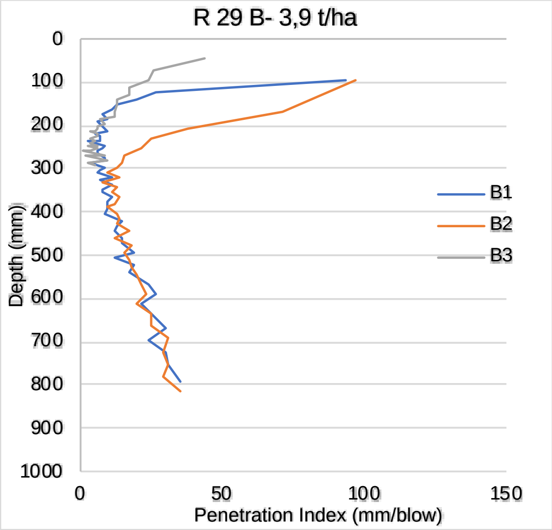

R 26 C- 2,7 t/ha

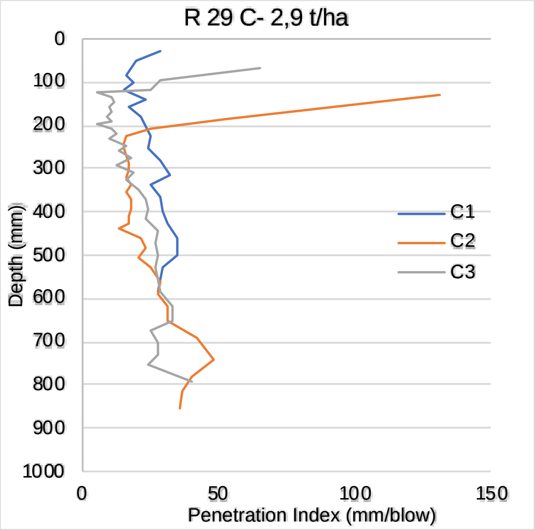

R 27 A- 3,8 t/ha

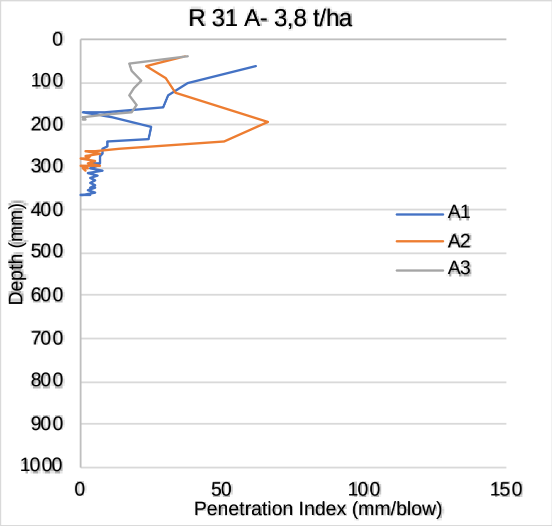

R 27 B- 4,3 t/ha

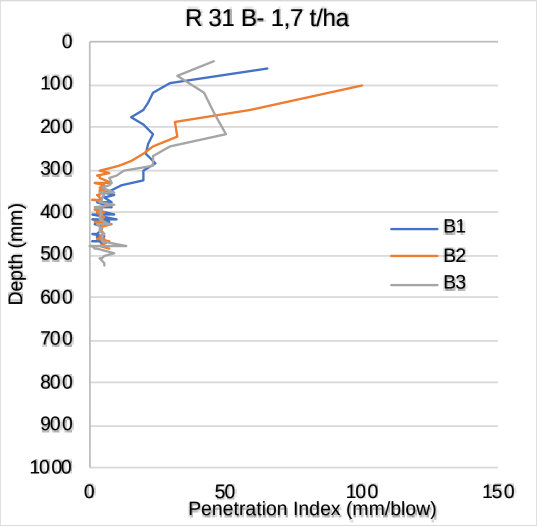

R 27 C- 4,7 t/ha

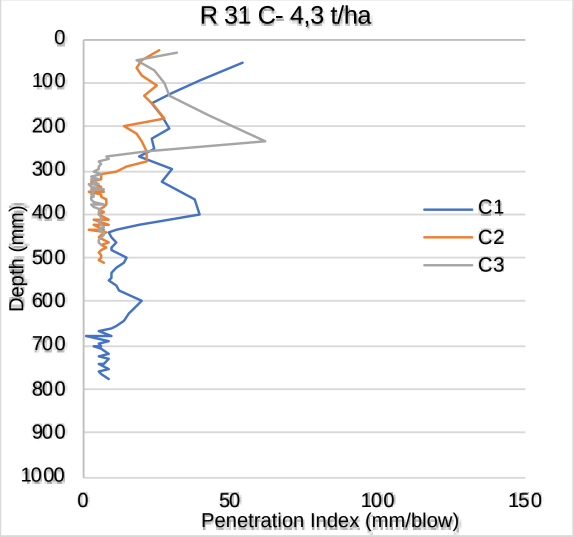

R 29 A- 6,1 t/ha


R 29 B- 3,9 t/ha


R 29 C- 2,9 t/ha


R 31 A- 3,8 t/ha


R 31 B- 1,7 t/ha


R 31 C- 4,3 t/ha