

# THE OCCURRENCE OF BLEACHED TOPSOILS ON WEAKLY STRUCTURED SUBSOIL HORIZONS IN THE WESTERN CAPE AND MPUMALANGA PROVINCES OF SOUTH AFRICA

By

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*Thesis submitted in partial fulfilment of the requirements for the  
degree Master of Agriculture at Stellenbosch University*



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December 2015

## **DECLARATION**

I hereby declare that the work contained in this thesis is my own original work and that I have not previously, in its entirety or in part, submitted it at any other institution for a degree.

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**ABSTRACT**

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Bleaching is a topsoil discolouration phenomenon recognised at family level within certain soil forms in the South African soil classification system. These topsoil horizons derive their name from the pale greyish colouration they exhibit in the dry state which is the result of the loss of pigmentation agents, specifically Fe oxides and organic material, from the upper part of the soil profile. In recent years, discrepancies regarding both the occurrence of bleached topsoils as part of weakly structured soil profiles in the South African soil landscape, and the description of this phenomenon in the national soil classification system, have become apparent. This has accentuated the clear lack of understanding which exists regarding the genesis of bleached topsoil horizons under weakly structured subsoil conditions in South Africa.

Based on the land-use and classification significance of this soil feature, this study aimed to provide clarity on the characteristics of bleached topsoils and some of the weakly structured subsoil horizons they overlie to determine by which mechanism these bleached topsoils develop and if the pedogenetic mechanisms are similar across two regions of South Africa. Due to soil colour's obvious importance as the only feature with which to recognise topsoil bleaching, an investigation into the measurement and expression of soil colour was also deemed to be important.

A total of 26 soil profiles were sampled throughout the Western Cape (WC) and Mpumalanga provinces. Colour was visually determined in the field using a Munsell soil colour chart and also by means of a spectrophotometer in the laboratory. A wide variety of soil chemical and physical properties were also determined for each sampled horizon. For comparison's sake, the selected soil profiles needed to represent profiles that could potentially qualify as having red/yellow-brown apedal B (*ferralsols*) or red/yellow neocutanic B horizons (*cambisols*), either with or without a perceived bleached topsoil (*achromic*). During sampling on the Highveld, bleaching was observed to be landscape related with bleached orthic A horizons only occurring on yellow-brown apedal B subsoil horizons at lower positions along the plinthic catenas. As a result, sampling on the Mpumalanga Highveld was conducted along catenal transects. In the WC, bleached profiles did not follow a noticeable landscape pattern and subsoils comprising both red and yellow weakly structured horizons were recorded.

Soil colour investigations proved Fe oxides to be the main pigmentation agents responsible for the expression of red- and yellow colours in the sampled soils, with soil samples also becoming redder with an increase in the Fe oxide content. Discrepancies were detected in the way soil colour was registered through human perception and spectrophotometer measurements. In general, the eye

perceived the soils to be brighter and more chromatic and therefore was less sensitive towards detecting bleached horizon colours.

The majority of the determined chemical and physical soil properties did not differ between the Western Cape and Highveld soils and did not show any relation to the bleaching phenomenon in either of the locations. In the Western Cape, profiles tended to have a greater water dispersible clay (WDC) phase, with the bleached Western Cape profiles proving to be even more unstable than the non-bleached variants. Iron oxide characterisation indicated proportionally similar amounts of crystalline and poorly-crystalline Fe oxides were present at both locations although in general bleached topsoils tended to have greater poorly-crystalline Fe contents. This trend was more pronounced in the Highveld profiles and was deemed to be indicative of a wetter soil moisture regime and alternating cycles of Fe reduction and oxide precipitation at this location.

The reported poorly-crystalline nature of the Fe oxides together with the observed landscape influences, suggest Fe reduction to be the pedogenetic process responsible for bleached topsoil horizons overlying weakly structured subsoils on the Mpumalanga Highveld. The strong association between bleaching and clay dispersibility in similar profiles of the Western Cape suggest clay eluviation to be a common pedogenetic process in these soils. The presented data in this study did not provide an explanation for how clay eluviation results in bleached soil colours and no evidence was obtained to enable conclusive statements regarding the role of Fe reduction and clay eluviation as independent or complementary processes responsible for bleaching in the Western Cape soils.

For the purpose of soil classification in South Africa, the inclusion of bleached orthic A horizons as family criteria in wetter variants of the yellow-brown apedal profiles is suggested. Based on the instability of the clay phase in the Western Cape profiles, it is proposed that these red or yellow weakly structured subsoils would be better classified as neocutanic B horizons and that bleached topsoils can in some instances be indicative of a more dispersive profile.



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## OPSOMMING

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Verbleiking is 'n bogrondverskynsel wat erken word op familievlak in die Suid-Afrikaanse grondklassifikasiesistelsel. Die benaming van hierdie verskynsel spruit voort uit die vaalgrys kleure wat hierdie bogrondhorisonte openbaar in die droëgrondtoestand, as gevolg van die verlies van grondpigmente soos Fe oksiedes en organiese materiaal uit die boonste gedeeltes van die grondprofiel. 'n Aantal teenstrydighede aangaande beide die voorkoms van gebleikte bogronde as deel van swak gestruktureerde grondprofiel in Suid-Afrika, sowel as die beskrywing van hierdie verskynsel in die nasionale grondklassifikasiesistelsel, het oor die afgelope paar jaar te voorskyn gekom. Hierdie teenstrydighede beklemtoon die beperkte kennis wat daar bestaan aangaande die pedogenetiese oorsprong van gebleikte bogronde op swak gestruktureerde ondergronde in Suid-Afrika.

Weens die implikasies van hierdie bogrondverskynsel vir gebruiks- en grondklassifikasie doeleindes, beoog hierdie studie om die eienskappe van gebleikte bogronde en sommige van die swak gestruktureerde ondergronde wat hul oorsake, te bepaal, om sodoende die genetiese oorsprong van hierdie gronde onder sulke toestande te probeer verklaar. As gevolg van grondkleur se belangrikheid as die enigste eienskap wat gebruik kan word om gebleikte bogronde te identifiseer, is aspekte aangaande die meting en uitdrukking van hierdie verskynsel ook as belangrik geag.

Altesaam 26 grondprofiel, verspreid oor die Wes-Kaap Provinsie en die Mpumalanga Hoëveld, is versamel. Grondkleur is eers visueel bepaal tydens veldwerk deur gebruik te maak van die Munsell grondkleurkaarte en later ook deur middel van 'n spektrofotometer in die laboratorium. 'n Verskeidenheid grondchemiese en -fisiese eienskappe is ook bepaal vir elk van die versamelde horisonte. Die gekose profiele moes van so 'n aard wees dat beide rooi/geelbruin apedale B of rooi/geel neokutaniëse B horisonte 'n klassifikasie moontlikheid kon wees. Profiele met en sonder gebleikte bogronde is ingesluit. Tydens die versameling van grondmonsters is dit waargeneem dat verbleiking op die Hoëveld landskap-gedrewe is, met gebleikte ortiese A horisonte wat slegs voorkom op geelbruin apedale ondergronde in die laer hellingsposisies van hierdie landskap. As 'n gevolg van hierdie waarneming, is grondversameling op die Hoëveld uitgevoer langs katena-transekte af. In die Wes-Kaap was daar geen merkbare verhouding tussen verbleiking en landskapposisie nie en die ondergronde van gebleikte profiele het bestaan uit beide rooi en geel swak gestruktureerde horisonte.

Die ondersoek na grondkleur het bewys dat Fe oksiedes die hoof grondpigment is in die rooi en geel gronde wat versamel is en dat gronde geneig was om rooier te raak soos wat die Fe inhoud van die monster toegeneem het. Verskeie ten opsigte van die wyse waarop hierdie uitgedrukte kleure

geregistreer word, is tussen die visuele en spektrofotometriese bepalinge waargeneem. Oor die algemeen het die oog die grondkleure as helderder en meer chromaties waargeneem en gevolglik was visuele kleurbepaling minder sensitief ten opsigte van gebleikte grondkleure.

Die meerderheid van die chemiese en fisiese grondeienskappe wat bepaal is, het nie verskil tussen die Wes-Kaapse en Hoëveld profiele nie en het ook geen verwantskap met verbleiking getoon in enige van die twee areas nie. Die Wes-Kaapse profiele het egter 'n groter waterdispergeerbare kleifraaksie (WDC) getoon, met die gebleikte profiele in die area wat as nog meer onstabiel as die nie-gebleikte variante bewys is. Die grond Fe inhoud in beide die Wes-Kaap en die Hoëveld het proporsioneel dieselfde vlakke van kristallyne en swak-kristallyne Fe oksiedes bevat, met die gebleikte profiele in geheel wat meer swak-kristallyne Fe oksiedes besit het. Hierdie tendens was meer prominent in die Hoëveld bogronde en is toegeskryf aan natter grondtoestande wat variërende fases van Fe reduksie en oksidasie tot gevolg gehad het.

Die swak-kristallyne Fe oksiedes tesame met waarnemings in die veld aangaande landskap en grondverhoudings, dui daarop dat Fe reduksie die meganisme is waardeur gebleikte bogronde op swak gestruktureerde ondergronde in die Hoëveld ontstaan. Die sterk verwantskap tussen verbleiking en WDC in soortgelyke profiele in die Wes-Kaap dui daarop dat klei-eluviasie 'n groot rolspeler in hierdie grondprofile is. Daar kon egter in hierdie studie geen bewyse gevind word wat aandui hoe klei-eluviasie gebleikte grondkleure veroorsaak nie. Verder kon Fe reduksie se bydrae tot verbleiking in die Wes-Kaap gronde nie uitgesluit of vasgestel word nie.

Vir grondklassifikasiedoeleindes word daar voorgestel dat gebleikte ortiese A horisonte as 'n familie-kriterium in die natter weergawes van die geelbruin apedale profiele ingesluit word. Verder, gegrond op die onstabiele klei fraksie in die Wes-Kaap profiele, stel ons voor dat hierdie swak gestruktureerde rooi en geel ondergronde as neokutaniëse B horisonte geklassifiseer word en dat in sommige gevalle, 'n gebleikte bogrond 'n aanduiding kan wees van 'n meer onstabiele grondprofiel.

*“Wees sterk, staan vas, begin die werk!  
Moenie bang wees nie en moenie besorg wees nie,  
want God die Here, my God, is by jou.  
Hy sal jou nie aan jouself oorlaat of jou verlaat nie,  
sodat jy al die werk vir die diens in sy huis kan afhandel.”*

*\*\*\**

*1 Kronieke 28:20*

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## ACKNOWLEDGEMENTS

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When tackling a project like this one, there is always an array of people that play a significant role in the outcome thereof, be it as a peer or colleague that assists you on the academic side or a friend or family member that keeps you sane amidst the chaos. Although I would like to mention you all and your contributions towards this study, I realise that adding another 20 pages to this thesis might be a bit impractical. Therefore, read the following words and where they apply to you, take credit, even if your name is not pertinently mentioned.

I would like to sincerely thank the following people:

Dr Catherine Elaine Clarke, your guidance, advice and simple answers to my many complex (and not so complex) questions is what made this study. Thank you for treating me like a colleague rather than a student, bouncing ideas off of me, valuing my opinion and in the process transforming me into a capable soil scientist with a real interest in pedology. For that, I owe you more than these mere sentences.

Dr Willem de Clercq, thank you for your willingness to help and the particular expertise you brought to this study. Even though some of the work that was done were not included in the final thesis, it does not mean that time was not put into it. It is dearly appreciated.

Dr Freddie Ellis and oom/Prof Jan Lambrechts. It has been a privilege working with and learning from some of the most knowledgeable pedologists in the country. Thank you for your assistance in the field and the advice you provided to both me and Cathy. Without you, this study would not have been a success.

Prof Martin Kidd, for his assistance with the statistics done in this study. Your patience, swift replies and simple explanations were of unmeasurable value.

Importantly, a project like this one is also never possible without funding. In that sense a special word of thanks must go to the National Research Foundation for providing me with a bursary during the course of these past two years.

The rest of the academic staff at Stellenbosch University's Department of Soil Science for your interest in and support of this project. Special thanks to Dr Eduard Hoffman and Dr Ailsa Hardie who were always willing to answer a quick question on physics or chemistry in my many hours of need.

To all the familiar faces in the soil science department who help create an enjoyable environment for all students to work in. Tannie Annatjie French and Tannie Delphine Gordon, for all the smiles

throughout the week and the tea on Fridays. Nigel Robertson, Matt Gordon and Herschelle Achilles, thank you for your assistance and advice in the laboratory and, of course, all the conversations on rugby and South African politics.

To all my fellow postgrad students with which I shared the department during the last two years. I thank each and every one of you for your advice, assistance and conversations, and wish you all the best for the future. In this regard, special mention must go to Marilee Carstens, who worked on the sister-project of this study, for her assistance in the field, her references, quick answers and bright memory in times when mine could not recall. Abraham Vorster and Michael Esmeraldo, for their non-academic chats in an overwhelmingly academic environment, and also Ockert Botha for taking over when these guys were not in the department anymore.

To everyone who assisted me during field work on the Mpumalanga Highveld in July of last year. Max and Jules Kane-Berman, thank you for your hospitality and the time and resources you took out of your days to aid me during this time. Also Dr Johan van der Waals, for your interest in the subject and the generosity with which you shared your equipment and knowledge.

Then, to my family, especially my parents, who have been patient with my studies for the past six years. My mother, who knows about my obsessions with work all too well and who always has the words to change my mood. My father, who always encourages me to take a break, take it slow and enjoy what I am busy with. If I had to dedicate this study to someone, it would be you two. My sister and brother-in-law, Marike and Hannes Spangenberg, for your support and love. Also to Marike for doing the marvellous graphics and illustrations for this thesis, as she has done for me during numerous other projects in the course of my university career.

My friends, who kept me busy over weekends and who keep on reminding me that life is not always as serious as I make it out to be. Your contribution to this study is unmeasurable and I count myself as truly lucky.

Lastly, to my Lord Jesus Christ, who provided me with the words of 1 Chronicles 28:20 at the start of this study. *Ek het die Here altyd by my: omdat Hy by my is, sal ek nie struikel nie.*

*“...only rarely have we stood back  
and celebrated our soils as something beautiful and perhaps even mysterious.  
For what other natural body, worldwide in its distribution, has so many interesting secrets  
to reveal to the patient observer”*

**-Les Molloy**, *Soils in the New Zealand Landscape: the Living Mantle*, 1988

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## INTRODUCTION

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In many systems of soil classification, the underlying principle is to group soils of similar genesis (Schaetzl & Anderson 2005). The recognised relationship between pedogenetic processes and expressed chemical and morphological features in the soil has meant that within global soil classification systems a variety of measureable and observable profile criteria have been specified which infer specific pedogenetic pathways and therefore also serve to group and categorise different soil types (Buol et al. 2011). Amongst the most basic of all soil morphological features used in soil classification and probably the characteristic that is most noticeable to all, irrespective of one being an earth scientist or layperson, is soil colour and the variations with which it can be expressed (Bigham & Ciolkosz 1993).

Within the South African soil classification system a number of diagnostic top- and subsoil horizons as well as some soil family varieties are recognised based on their colour characteristics (Soil classification working group 1991). In relation to other systems of soil classification, South Africa makes use of very specific and strictly defined colour criteria for horizon delineation. The five diagnostic horizons with specified Munsell colour ranges are the red and yellow-brown apedal B, the red structured B, the diagnostic E and the melanic A horizon. In addition, recognition is also given to another colour-related soil feature termed bleaching. Bleaching refers to a topsoil discolouration phenomenon that was first described and termed by Northcote (1979) in Australia. Under South African conditions bleaching is recognised in diagnostic orthic A topsoil horizons and is a feature distinguished at family level within certain soil forms (Soil classification working group 1991). Bleached horizons derive their name from the pale greyish colouration they exhibit in the dry state (Munsell colours as defined for the diagnostic E horizon) which is the result of the loss of pigmentation agents, specifically iron oxides and organic material, from the upper part of the soil profile.

The accepted and most widely documented mechanism proposed for the genesis of bleached topsoils is related to water saturation, Fe reduction and the consequent stripping of Fe oxides from the soil mineral particles (Soil classification working group 1991; Fritsch & Fitzpatrick 1994; Cox et al. 1996; Peterschmitt et al. 1996). In soils where such a pedogenetic process is active, the most important component besides an oxidizable carbon source and a sufficient quantity of Fe oxide minerals, is the anaerobic conditions brought about by water saturation. Under these conditions, the microbial-driven mineralisation of organic matter makes use of ferric Fe as an alternative electron acceptor, which is reduced to mobile ferrous Fe. The ferrous Fe phase is washed out of the profile with subsequent rainfall events and a bleached horizon colour is perceived in the zone of removal (Peterschmitt et al.

1996). Currently, Fe reduction and to a lesser extent podsolization, are the only recognised modes of origin for these pale-coloured topsoils in the literature (Soil classification working group 1991). As a result, bleaching is predominantly deemed to be a hydromorphic soil feature. No specific recognition of this characteristic under such soil conditions is given in the South African soil classification system (e.g. bleached orthic A overlying a diagnostic E or G horizon).

Although the well-known relationship between soil hydrology and landscape morphology is most commonly used to explain soil drainage conditions (van Tol et al. 2011), soil characteristics such as textural and structural contrasts between the top- and subsoil horizons have also been shown to result in saturated conditions (Chittleborough 1992; Cox & McFarlane 1995; Cox et al. 1996). It is therefore not surprising to note that it was on texture-contrasted duplex soils that Northcote first made record of topsoil bleaching. This phenomenon is also acknowledged in the current South African classification system where bleached topsoils are recognised in certain soil forms containing diagnostic prisma-cutanic and pedocutanic B horizons. Although these horizons by definition have not undergone marked reduction (Van der Waals 2013), such duplex profiles consisting of subsoil horizons with enriched clay contents and stronger structure tends to restrict water infiltration which can promote saturation and Fe reduction (Tennant et al. 1992). A similar mechanism of bleaching is also conceivable in profiles containing lithocutanic B horizons where weathered saprolitic material can impose a restriction to water infiltration. Considering the apedal structure of the neocutanic B diagnostic horizon, the definition and specified characteristics of these subsoil horizons propose no plausible explanation for how water saturation and Fe reduction can occur in the upper parts of such profiles. The fact is that within the South African soil classification system (Soil classification working group 1991), bleaching is recognised in profiles containing diagnostic subsoil horizons that have not undergone marked reduction but no explanations are provided as to how bleaching would originate under these conditions. Van der Waals (2013) hypothesises that for some profiles comprised of such subsoil horizons, topsoil bleaching was probably included in the current national classification system to accommodate lighter coloured horizons that developed as a result of clay eluviation.

The reported occurrence of bleached topsoils on red/yellow-brown apedal subsoil horizons (Van der Waals 2013) is equally difficult to explain. Taking into consideration the poor structural development and uniform colouration of the red and yellow-brown apedal B diagnostic horizons it is presumed that these subsoils represent a well-drained soil condition that provide little or no restriction to water infiltration (Soil classification working group 1991; Fey 2010). This implies that no temporary waterlogged conditions resulting in Fe reduction and loss is presumed to occur and therefore bleaching as a result of this mechanism is not expected in topsoils overlying these apedal subsoil horizons. Observations made by Van der Waals (2013) on the Mpumalanga Highveld recorded orthic

A horizons, showing a bleaching tendency, overlying yellow-brown apedal B subsoils. Similarly, Nell & Dreyer (2006) documented the same phenomenon in parts of the Lowveld. Of course such a horizon sequence is not included in South Africa's soil classification system simply because it is in stark contrast to the current understanding of these well-drained subsoil horizons.

The constraints imposed by a misinterpretation of soil features, such as topsoil bleaching, on soil classification and effective land-use is unavoidable. From a land-use perspective, bleached topsoil horizons are deemed inferior to their non-bleached counterparts. This is a result of their tendency to exhibit signs of physical instability and crusting, as recorded by Ellis (1988) on soils studied in the Karoo. In addition, physical instability is also proposed to make these soils more prone to erosion and therefore less suitable for sustainable long-term cultivation. This was elucidated to by Tennant et al (1992), who described bleached topsoils as having a more fragile structure and consequently an increased sensitivity to destruction through cultivation or even raindrop impact. The overall widespread nature of bleached topsoils in South Africa and their part as essential components of hillslope hydrology (Van der Waals 2013) necessitates the importance of the correct identification and classification of such horizons. This is not only for efficient agricultural land-use but also for accurate hydrological modelling along soil toposequences and resourceful catchment management. Due to the fact that bleaching is not holistically accounted for in the SA classification system, soils showing this phenomenon are classified in a variable manner, something that is not only scientifically inappropriate but more importantly, can result in the mismanagement of soil resources.

The anomaly regarding the occurrence of bleached topsoils as part of weakly structured soil profiles has meant that soil surveyors have been allowed to subjectively prioritise certain soil characteristics within the confines of South Africa's soil classification system. More specifically, classification can follow one of two routes: a red or yellow-brown apedal B horizon is recognised based on the apedal characteristics of the subsoil horizon with disregard for the bleached topsoil, or the bleaching phenomenon in the topsoil is proposed to be a result of an unstable clay phase thereby directing subsoil classification towards more dispersive neocutanic B horizons upon which these discoloured topsoils are recognised as a family variation in the current classification system. In the Western Cape one of the hypothesis is that due to the mature age of the landscape and its soils (Hendey 1983), the present Fe oxides are extremely crystalline and therefore less reactive and capable of stabilising the clay phase (Bech et al. 1997; Duiker et al. 2003). As a result, it is suggested that bleached topsoil colours develop due to clay migration down the profile. The fact is however that this has never been proven and no information exists to indicate if such tendencies are also present in other parts of the country where bleached topsoils have been recorded.

Nonetheless, the fundamental issue remains that similar soil entities are given different names and are observably under- or over valued by different soil scientists as a result of the deliberate omission of certain profile characteristics. Van der Waals (2013) emphasizes the negative implications of classification based on topsoil morphology particularly pertaining to the use of colour satellite images or aerial photographs in soil group delineations. Such actions predominantly make use of topsoil colour for soil classification meaning that in scenarios where bleached topsoils overlie certain agriculturally-suited apedal subsoil horizons, classification based on the bleaching of the topsoil will result in soil entities with underestimated land-use value simply because the national soil classification system does not recognise such a sequence of horizons.

### Aims and objectives

A clear lack of understanding exists regarding the genesis of bleached topsoil horizons in South Africa. This is accentuated by i) the recorded occurrence of bleached topsoils overlying perceptually well-drained, weakly structured subsoil horizons on the Highveld, and ii) the unexplained inclusion of the bleached family criteria in profiles that have not undergone marked reduction in the national soil classification system. In addition, the existence of different hypothesis with regards to the pedogenetic origin of these pale coloured topsoils in different parts of the country, and the above-mentioned land-use and soil classification significance of this feature, have all provided the rationale for commencing with this study. Thus the overall aim of this study was to establish the pedogenetic processes responsible for the bleaching of topsoils occurring on weakly structured subsoils of the Western Cape and Mpumalanga Highveld in order to make recommendations for the classification of such soils. To realise this central aim the following research objectives were set:

- i. Establish the factors effecting colour measurement, in particular the difference between visually perceived and spectrophotometrically measured colour as well as the effect of wetness on colour observation
- ii. Establish how colour correlates to physical and chemical properties of red and yellow-brown soils
- iii. Determine the chemical and physical differences in bleached and non-bleached profiles from the Western Cape and Mpumalanga Highveld in order to make inferences on the mechanisms involved in topsoil bleaching in these two regions
- iv. Based on the findings of the above objectives make recommendations on the classification of weakly structured profiles exhibiting bleached topsoil colours



### Thesis layout

This study is divided into five chapters. The first chapter is a general literature review on the different aspects of soil colour and will only provide a review of the general science behind colour, its applications in soil science and the relevance thereof as a morphological property. The different mechanisms for soil colour description, measurement and quantification recognised in the literature will also be discussed. Chapter 2 describes the sample collection and analyses procedures used in the study. Chapter 3 focusses on the first two objectives set for this study, consequently dealing with soil colour expression and measurement. The fourth chapter comprises the investigation into the mechanisms of bleaching and satisfies the third study objective. The fifth and final chapter provides the general conclusions of the study, the possibilities for future research and recommendations for soil classification in South Africa and is therefore structured around the last objective (iv).

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## CHAPTER 1: THE COLOUR OF SOIL

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### **1.1. Introduction**

The colour of a soil is one of its most apparent morphological features and one that, according to Bigham & Ciolkosz (1993), is often among the first properties recorded by earth scientists in the field and commonly also the only characteristic that would be of any significance to a layperson. In a literal sense, soil colour has little worth. It is the relationship that exists between expressed soil colours and certain profile characteristics, some of which are important for soil interpretation and classification, that accentuate the importance of recognising this soil feature (Melville & Atkinson 1985; Post et al. 1993). In all the major soil classification systems soil colour is used as diagnostic criteria for horizon identification with colour serving as a tool extensively used by soil scientists for the rapid approximation of soil properties, function and condition (Viscarra Rossel et al. 2006). The widely recognised reality however remains that the colour of a soil and human perception thereof is somewhat arbitrary (Melville & Atkinson 1985; Post et al. 1993; Sánchez-Marañón et al. 2011). This, in part, is the result of the methods used for soil colour determination and the need that exists for these methods to be practical and suited for in-field application. Regardless, soil colour constitutes a very useful soil property that is without a doubt complex, but also one that soil scientists cannot afford to overlook.

In South Africa, where the local soil classification system makes use of very strictly defined colour criteria for many of the diagnostic horizons (Soil classification working group 1991), recognising and understanding the challenges associated with soil colour is vital. This chapter is therefore aimed at providing some insight into the general science behind colour, its applications in soil science and the relevance thereof as a morphological property, to equip the reader with a better understanding of what soil colour represents and how it should be dealt with. The different mechanisms for soil colour description, measurement and quantification recognised in the literature will also be discussed.

### **1.2. Colour fundamentals**

Light is generated by means of three-dimensional oscillations that move outward from a source. These oscillations represent waves which in simple terms can be defined as a transmission of energy from one source to another. Light waves are electromagnetic (EM) of nature which means the oscillations are of the movement of electric-magnetic fields. These EM waves can be quantified by a frequency, wavelength, speed, and phase and based on the differences in the wavelengths of these EM waves, a range referred to as the electromagnetic spectrum is defined (Fortner & Meyer 1997).

Visible light constitutes a small portion of the overall EM spectrum and is represented by EM waves with wavelengths of between approximately 400 nm to 700 nm (usually with a frequency of about  $10^{15}$  Hz). Quantum mechanics dictates that light can be described as either a wave or a particle. When referring to light as particles, the term photons are used. A photon is defined by Fortner & Meyer (1997) as a tiny, massless particle of light that has a definite wavelength, frequency, speed and energy. The frequency of a photon will determine the amount of energy it carries. Colour is a term synonymous to light which refers to the particular frequency of such a wave/particle phenomenon. In pure theoretical terms, colour is a description of the wavelength, frequency and correlated energy capacity of light photons. This definition, although scientifically correct, omits an essential component of colour that is significant to everyday life and probably the most important to all interested in understanding and objectively quantifying this phenomenon. For any observer colour is a perception and how it is perceived is influenced by a number of factors. The definition by Ball (2009) encapsulates this aspect through describing colour as the fundamental perception of different wavelength-light intensities by the human eye.

To comprehend why referring to colour as a perception is so important one has to understand how colour is processed by the eye-brain system. Fortner & Theodore (1997) explains the process very simplistically based on the morphology of the human eye and the functionality of its components. The three parts of the eye that is most important for sight include: 1) the cornea – which is the lens of the eye, 2) the retina – which contains millions of photosensors that are responsible for the detection of light energy and 3) the iris – which controls the amount of light energy which will enter the eye. The photosensors in the retina are activated when a chemical known as a photopigment absorbs a photon, this in return generates an electrical nerve impulse signal to the brain and colour is perceived. The registered colour therefore depends on the wavelength distributions of the energy entering the eye and the response of the eye-brain system to this energy (Edwards 1975). In colour science it is, however, well known that the response of the retina can differ from one person to the next resulting in colour being perceived differently by different observers (Edwards 1975).

Melville & Atkinson (1985) state that in addition to the individual response of the human eye to variable spectral characteristics, the perceived colour of an object is also influenced by the spectral characteristics of the light source illuminating the object and the reflectance properties of the surface of the object.

### ***1.3. The colour of soils***

Objects do not emit colour but rather absorb or reflect light of different wavelengths in varying amounts. This reflectance off the surface of an object dictates what wavelength distributions of energy

reaches the retina and what colour will be perceived (Ball 2009). Soil consists of a combination of chemical and mineralogical components each affecting what wavelengths of light are absorbed or reflected from the surface of the soil particles (Rabenhorst & Parikh 2000; Sánchez-Marañón et al. 2004). As a light beam enters into the soil mass it undergoes multiple stages of reflection and diffraction, with the reflected or scattered light that returns from the surface of the soil mass determining the particular colour that is recognised by the human eye (Torrent & Barron 1993).

Sánchez-Marañón et al. (2004) summarizes the main pigmentation agents responsible for soil colour as i) organic matter (black), ii) Fe oxides and hydroxides (red to yellow) and iii) silicate and carbonate minerals (white to grey). According to Barron & Torrent (1986) the soil matrix, which usually consists of minerals such as quartz, feldspars and different clay fractions, is predominantly white and considered to be a single pigment, whilst the various natural organic or chemical pigments within the soil range from yellow to red to dark brown or black and can either occur with the mineral grains or as coatings upon the mineral surfaces (Rabenhorst & Parikh 2000). In addition to organic matter and Fe oxides, other pigmenting agents such as manganese oxides also exist and can be present as dark brown or black coatings, nodules or concretions but are generally found in such small amounts that they make less of a contribution to soil colour in general (Rabenhorst & Parikh 2000). Accordingly, it can be concluded that the baseline colour for any soil with no added organic or chemical pigmentation agents will be white to grey based on its constituent minerals, with any addition of Fe and/or organic matter in variable combinations resulting in a deviation from this standard colour condition (e.g. Torrent et al. 1983). The colouration effect of the main soil pigmentation agents is to a large extent determined by the strength of their pigmenting influence (Torrent et al. 1983), the size of their surface area (Sánchez-Marañón et al. 2004), their position in the profile (Viscarra Rossel et al. 2006) and of course their relative abundance within the solum (Baumgardner et al. 1985; Rabenhorst & Parikh 2000).

In addition to these specific pigmenting substances, various authors have also recognised other soil characteristics that influence spectral reflectance and therefore perceived soil colour. Bowers & Hanks (1965), Baumgardner et al. (1985), and Torrent & Barron (1993) all concluded that particle size and soil moisture can significantly alter how light is reflected from the soil surface and therefore how colour is perceived by an observer. According to these authors the presence of water molecules results in a liquid layer around individual soil particles which decreases soil reflectance and results in an observable darkening effect (Post et al. 2000; Viscarra Rossel et al. 2006). Soil moisture content is therefore widely recognised as a determinant of soil colour (Wheeler et al. 1999) with the addition of water resulting in a deviation from the dry soil colour condition.

The physical nature of soil particles is recognised as another factor influencing soil colour (Sánchez-Marañón et al. 2004). Soil particle size and aggregation are amongst the physical parameters that are most significant. Bowers & Hanks (1965), Baumgardner et al. (1985), Torrent & Barron (1993), Sánchez-Marañón et al. (1997), and Sánchez-Marañón et al. (2004) all reported that in the absence of any confounding pigmenting agents on the soil particle surfaces, a soil tends to become lighter with decreasing particle size. This is explained by Baumgardner et al. (1985) and supported by the findings of Bowers & Hanks (1965) as being a function of surface roughness. Finer particles will fill a volume in a more uniform manner forming a more even surface which will limit internal light absorption and enhance light reflection by the soil body. Noticeably, an accumulation of quartz in the coarse fragments of soil (>2 mm) can however cause an opposite effect as shown by Post et al. (1994) where recorded colours were actually darker in the quartz-free fine soil fraction (<2 mm). In the presence of pigmenting agents such as organic matter, carbonates and Fe oxides, Sánchez-Marañón et al. (2004) hypothesised and tested whether smaller soil particles with greater surface area will have a greater influence on soil colour than more coarser fragments. This was based to some extent on the findings of Scheinost et al. (1999) who concluded that Mie scattering (a scattering phenomenon where the wavelength of the scattered light is small in comparison to the size of the object) is responsible for the reddening and darkening of low-reflectance soils following a decrease in particle size. Results indicated that the fine sand and clay fraction made the most significant contributions to the colour of the soils under investigation, verifying the author's hypothesis. Based on the size of the reactive surface of smaller particles, it is expected that a larger area exists for pigments to coat and consequently the influence of smaller particle sizes towards soil colouration to be more significant. Where pigmenting agents occur as coatings on soil particles, particle size can therefore have a contrasting colouration effect as initially reported. Instead of causing lighter colourations, smaller particles can adsorb more of a pigmenting substance onto their surface area which can result in a more pronounced expression of colour. In addition Sánchez-Marañón et al. (2004) also aimed to study the effect of aggregation on soil colour. Following soil disruption through dry sieving, immersion wetting and ultrasonic energy, soils showed a strong tendency to become lighter. The authors concluded that aggregation resulted in darker soil colours which becomes progressively lighter as aggregates are destroyed.

An interaction of all the above mentioned influences mean that the variations of colour expressed in a soil cannot be explained by only considering a single one of these factors. Sánchez-Marañón et al. (2004) state that the interactions between the features responsible for the colouring of soils are too complex to allow for any definitive model to be established. Following the scientific approach of these authors, it would seem that the only way to essentially determine what factors are responsible for the

colouration in specific soils, confounding variables need to be dealt with and all processes that can have a potential influence on the colouring condition need to be individually accounted for.

A first step in this regard would be to inspect the processes dictating the condition in which pigmentation agents are present in the soil and that are essentially responsible for the expression of colour via these pigmentation agents. The complexity of these processes will differ, but this has no effect on their significance seeing that a better understanding of pigmentation processes might help to explain the expressed soil colours more effectively. The nature of organic matter deposition is a good example. Organic matter is the main cause of darker soil colours but due to the predominant accumulation of organic matter in surface horizons, subsoil colour in general is less affected by organic matter in comparison to topsoil horizons (Rabenhorst & Parikh 2000). In subsoil horizons, Fe oxides are generally regarded to be the most prominent colouring agent (Torrent et al. 1983).

Soil hydrology also has a well-documented influence on soil colour through one of two pathways, depending on the state of saturation. Under unsaturated conditions, water stored in the soil pores is referred to as soil moisture (Seneviratne et al. 2010) and its influence on soil colouration has been previously discussed. Under more saturated conditions, water can induce chemical processes such as redoximorphism which serves to establish colouration patterns associated with zones of Fe oxide accumulation and depletion (Wheeler et al. 1999; Rabenhorst & Parikh 2000).

Redoximorphism is the result of the periodic water saturation of a soil which generates anaerobic soil conditions (Rabenhorst & Parikh 2000). Insoluble ferric Fe serves as the electron acceptor and is reduced to soluble ferrous Fe, which can easily be translocated to other positions within the soil profile. This mobilization of Fe causes zones of Fe depletion and Fe accumulation to develop within soils, each with an identifiable colour. The removal of Fe will result in low chroma, white to grey colours typical of uncoated mineral grains developing in the depleted zones whereas the transported Fe will, following the subsidence of water saturation, be oxidized to form masses or coatings of redder or browner Fe oxides in the zones where they have been deposited (Vepraskas 1992). Rabenhorst & Parikh (2000) found, however, that these colour changes and the tendency of red soils to form such low chroma redoximorphic features can vary between different soils and the conditions under which they formed or occur.

The two most abundant secondary Fe oxides present within soil that are responsible for soil colouration are goethite and hematite (Torrent et al. 1983; Schwertmann & Taylor 1989). The presence of goethite within soils is usually indicated by yellower colours (10YR to 2.5Y Munsell hue) (Munsell color company 1975), whilst hematite is responsible for the more redder colours (7.5YR and redder) (Davey et al. 1975; Biggam et al. 1978; Torrent et al. 1983). Various studies have proven

hematite to be a much stronger pigmenting agent than goethite, with red colours often masking the yellow colours of goethite or only small quantities of hematite being required to give soil a predominantly reddish appearance (Childs et al. 1979; Torrent et al. 1983; Barron & Torrent 1986). Bigham et al. (1978) in addition concluded that the concentration, crystallinity and particle size of Fe oxides can also affect the contribution of these minerals to soil colour.

Using the Sánchez-Marañón et al. (2004) study as an example it can be seen that in order to explain the colour of a soil and the contribution of each factor to that what is being perceived, the interaction of different pigmenting features needs to be accounted for. These authors were interested in the contribution of different soil particle sizes to colour but recognised beforehand that in order to come to a conclusion, they needed to minimise the influence of organic matter, carbonates and free Fe oxides as pigmenting agents. Only after this step was taken could a definitive statement about the contribution of particle size fractions to soil colour be made. In conclusion it seems that to be able to methodically explain the colouration patterns within a soil, potential processes responsible for different soil colours must be identified, additional variables that might cause colour deviations in this regard must be recognised and the interactions of all these factors must be accounted for. This of course is what makes the study of soil colour such a complex subject within field of soil science.

#### ***1.4. The relevance of soil colour***

Following the declaration of what mechanisms and main pigmentation agents are influential to soil colour and what approach should be taken in explaining colouration patterns, the obvious next questions will be what does soil colour mean and what is the relevance thereof within the soil system? The first important distinction to make is that soil colour is of no direct agricultural significance (Young 1976). The value of colour in soils is based purely on its strong correlation with particular soil properties and processes that are in most instances applicable to land-use (e.g. van Huyssteen & Ellis 1997).

Viscarra Rossel et al. (2006) lists soil colour as a good indicator of soil drainage, aeration, organic matter content and fertility. Darker surface soils for instance, which as previously mentioned are predominantly indicative of high organic matter contents, are shown to be more fertile and accordingly more suitable for plant growth (Schulze et al. 1993). It is, however, colour's relation to drainage (and to some extent topography) that has probably enjoyed the most research attention. Soil colour indices have been developed in numerous studies to assign drainage classes to specific soils and particularly in soils rich in Fe minerals because distinctive colour variations can be observed as a result of differences in drainage conditions (Van Huyssteen & Ellis 1997; Rabenhorst & Parikh 2000; Van Huyssteen et al. 2010). Various authors including Torrent et al. (1983), Barron & Torrent (1986)

and Gobin et al. (2000) were also able to use colour to differentiate and quantify iron oxide content in soils. From these studies it is implied that in Fe rich soils, information regarding the pedological processes and properties applicable to a particular profile can be obtained by interpreting the colour features of the different soil horizons.

The presence and duration of waterlogging and its link to soil colour has been the focus of many studies. This is due to waterlogging's recognisable influence on soil colour as a result of the induced cycles of Fe reduction and oxidation related to oxygen availability (Wheeler et al. 1999; Rabenhorst & Parikh 2000) as well as other processes such as clay eluviation or nutrient leaching within the soil. Blavet et al. (2000) found that the perceived redness of a soil is strongly correlated to the mean annual rate of soil waterlogging. Megonigal et al. (1993) and Thompson & Bell (1996) have used colour to quantify and assign particular drainage classes to certain soils. Jien et al. (2004) studied the relationship between measurable soil colour intensity and soil wetness, and also found significant correlations in undisturbed horizons. Van Huyssteen et al. (2010) correlated long-term water duration with colour and a range of other soil morphological features. These authors, in agreement with the results recorded by van Huyssteen et al. (1997), concluded that the strict colour criteria that exist for various diagnostic horizons in the South African soil classification system are accurate in indicating the typical duration of water saturation that would be expected in such profiles or horizons. A number of other examples demonstrating the existence of a relationship between colour and water saturation also exist as cited by Blavet et al. (2000) and include studies by Franzmeier et al. (1983), Evans & Franzmeier (1986), Mokma & Cremeens (1991) and Mokma & Sprecher (1994). Many authors have also recorded similar colour variations along hill slope toposequences, indicating similar aeration and drainage conditions at particular positions (Van Huyssteen et al. 2010; Blavet et al. 2000). The prescribed practice however, still remains that soil colour, rather than generalisations based on topographical positions must be used to infer waterlogging conditions (Blavet et al. 2000). From the literature it seems possible to state that categorical colour distribution patterns are the sole morphological indicator of soil drainage conditions.

The significance of using soil colour as an indication of drainage conditions is related to the influence of water saturation on the soil system. Van Huyssteen & Ellis (1997) postulated that an increase in water saturation causes an increase in the degree of weathering of the soil clay fraction which can have adverse consequences on for instance the exchange capacity of the soil. In addition, the tolerance of certain crops to soil wetness implies that by interpreting colour characteristics, a soil's suitability for the cultivation of particular crop types can also be determined (Van Huyssteen & Ellis 1997). Uniform red or yellow colours are indicative of iron oxides and develop in the soil solum under

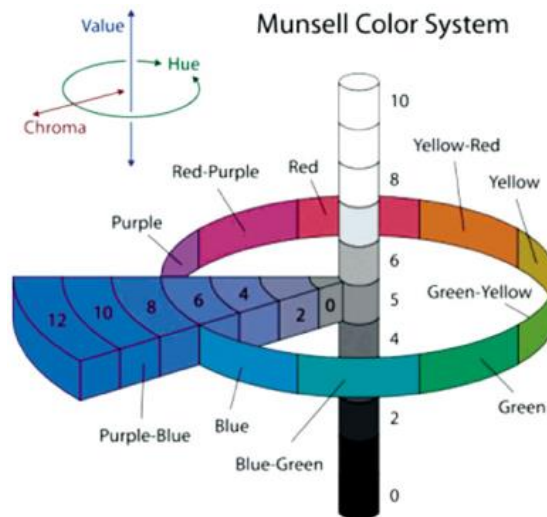


well-drained conditions. These oxides are known to increase clay stability, thereby limiting erosion and clay eluviation, both of which are undesirable in most land-use applications.

It is evident that colour, due to its representation of soil properties and processes related to drainage, fertility and organic matter content, is an extremely useful tool in soil classification. According to Blavet et al. (2000), it is the ease with which soil colour can be measured and the stability of colour over time that collectively contributes to its inclusion as a diagnostic feature in many soil classification systems. However, colour measurement is not trivial and Melville & Atkinson (1985) state that 'it is true that a designation of soil colour can be obtained very easily, but such a designation can be inaccurate and imprecise if the colour is determined carelessly'. The different factors applicable to soil colour means that the determination and quantification thereof is anything but straight forward. Despite these difficulties the fact remains that colour can be a soil morphological feature extremely relevant to land-use decision-making if interpreted correctly.

### ***1.5. The description and measurement of soil colour***

Soil colour is most commonly and conveniently measured by means of comparison with colour charts. The most popular and frequently used is the Munsell soil colour chart (Munsell Color Company 1975), an extract from the complete Munsell Book of Color (Munsell Color Company 1980). The system comprises of nine charts which collectively display 322 different colour chips organised in such a manner that a range of perceived colours is expressed along adjacent positions within the chart. This arrangement of the chips and the particular position of a colour within the chart are described by means of a three-dimensional notation that comprises of Munsell hue, value and chroma. In combination, all three of these parameters represent the Munsell colour space, which is simplistically described as a cylinder consisting of a central vertical axis. The vertical axis represents Munsell value, which is a measure of the lightness of a colour and which ranges from 1 at the bottom (darkest) to 9 at the top (lightest). Munsell hue refers to the qualities by which we differentiate between different colours and represents an indication of a colour's relation to red, yellow, green, blue or purple. In the Munsell colour space, hue constitutes the outer margins of the cylinder, with different colours being represented by means of an angular displacement from an arbitrary position on the central axis. The final parameter, Munsell chroma, is an indication of the strength or intensity of a colour. It is portrayed as the distance from the central axis.



**Figure 1.1.** The Munsell colour space model (source: <http://commons.wikimedia.org/wiki/File:Munsell-system.svg>)

Within the Munsell soil colour book itself, each one of the pages comprises of colour chips of the same hue. These hues represent different combinations of red (R), yellow (Y), blue (B) and green (G) and include 10R, 2.5YR, 5YR, 7.5YR, 10YR, 2.5Y, 5Y as well as two pages for gleyed soil colours (5Y, 5GY, 5G, 5BG and 5B). On every page the colour chips are arranged so that value increases from the bottom to the top and chroma increases from left to right. By matching the colour of a soil with a particular colour chip, the soil's colour can be described in terms of a hue, value and chroma unit which are collectively referred to as a Munsell notation.

The relative simplicity and ease with which colour can be measured using the Munsell system has meant that various colour observers across different industries and sciences, including soil science, have adopted it as the standard method for interpreting colour (Torrent & Barron 1993). However, for soil colour description, various authors have identified a range of disadvantages to this system. Although the Munsell system allows us to describe a colour in three dimensions, these measurements are subjective. Colour under these circumstances represent a sensory perception and the accuracy with which it can be measured can be influenced by a variety of factors such as those summarised by Edwards (1975). Spatial factors including colour constancy, contrast and spreading as well as temporal factors such as after images, flickering effects and colour blindness are amongst the issues discussed by this author. Torrent & Barron (1993) similarly state that because Munsell colour measurements are based on visual perceptions, various psychophysical and physical factors can cause substantial errors and therefore subjective results. Melville & Atkinson (1985) list a number of features that can influence what colour an object is perceived to be: 1) the incident angle of the light source relative to the viewing angle of the object, 2) The glossiness of the object's surface 3) the size, shape and distance of the object, and 4) colour contrasts between the object and its surroundings. In a study by Shields

et al. (1966) the authors concluded that soil colours can rarely be perfectly matched to Munsell colour chips and that if soil colour is to continue to serve as diagnostic criteria in soil classification, a more precise method of colour measurement must be adopted. Barrett (2002) states that “limitations of visual measurement techniques result in poor correlation between soil color and many soil properties”, which is particularly relevant to the objectives of this study. Therefore even minor errors in colour determination can result in the misidentification of soil horizons and incorrect conclusions about soil properties. Melville & Atkinson (1985) stated that the methods and conditions used for soil colour measurement must as a result be specified to ensure greater precision and accuracy. These authors recognised the marvel of the Munsell system and stipulated that associated problems are more related to measurement errors than system faults. In short, the recommendations by Melville & Atkinson (1985) for optimal soil colour measurements using the Munsell colour charts entail: 1) use more than one colour observer, 2) prepare all comparative samples in a standardised manner, 3) apply standardised illuminating conditions preferably approximating illuminant D65, 4) use Munsell colour charts together with the appropriate viewing masks, and 5) adequately report the details of the colour measurement procedures that were followed.

An important component listed in the above mentioned recommendations, and probably one of the main focusses of the Melville and Atkinson paper is that of the lighting conditions under which colours, by means of visual comparison with colour charts, are measured. Based on the fact that different light sources will differ in terms of the relative power or luminosity radiated at each wavelength within the visible spectrum, the spectral power distribution for light sources used in measuring colour has been described and specified by an organisation known as the CIE (International Commission on Illumination - Commission Internationale de l’Eclairage) (Melville & Atkinson 1985). According to the CIE, the standard illuminant D65 should be used for Munsell soil colour interpretations seeing that it is a close approximation of standard daylight conditions (CIE 1971). To explain why the illuminating source is so important one must first be reminded that different coloured objects will have different spectral reflectance characteristics. This also applies to soils and the particular colour chips they are compared to. The eye-brain system is able to achieve an approximate match between the soil and the colour chip regardless of the differences in their reflectance characteristics under specific lighting conditions. With a change in the illuminating source the colour of objects may no longer match due to a difference in luminosity of the light source. This phenomenon is termed metamerism (Melville & Atkinson 1985; Torrent & Barron 1993) or paramerism (Sánchez-Marañón et al. 2011) and is probably the mayor cause of inaccurate Munsell colour descriptions. A study conducted by Sánchez-Marañón et al. (2011) concluded that colour measurements in field under variable daylight conditions are

seldom accurate and that different Munsell notations will therefore be recorded for the same soil sample under different daylight conditions.

When contrasting all of the above mentioned recommendations and results with the relatively uncomplicated manner in which we view and use the Munsell colour system as soil scientists, it becomes clear that soil colour measurements require compromise either on the side of in-field practicality or scientific precision. Following the recommendations for scientifically optimal colour measurements by means of the Munsell colour chart by Melville & Atkinson (1985), critique can be given against almost each of the required components in terms of their practicality. Torrent & Barron (1993) for instance stated that using more than one observer for more accurate visual colour estimation is both impractical and very time-consuming. Similar in that regard is the use of viewing masks. Although the efficiency of using such apparatuses is known, most soil scientists do not even have them much less use them. Lastly, and probably the most influential factor is that of lighting conditions. Following the illuminant specifications developed by the CIE and mentioned by Melville & Atkinson (1985) it becomes apparent that soil colour cannot be optimally determined in the field. In order for colour measurement under D65 lighting conditions to occur, samples would have to be taken back to the laboratory. This of course is close to impossible under most circumstances, even more so in South Africa, where the soil classification system makes use of very strictly defined colour criteria for horizon identification (Soil classification working group 1991) and detailed mapping is sometimes done over extensive areas of land.

To enhance the in-field practicality of colour measurement by means of visual comparison against Munsell colour chips, the above mentioned recommendations need to be combined with what is practical and feasible for the soil scientist in the field. The most serious problem to overcome is lighting conditions and although no recommendations can be made to enhance accuracy, precision can potentially be improved by standardising colour measurement procedures. Melville & Atkinson (1985) list a number of illuminant conditions that a colour observer must be aware of and try to avoid. Firstly, accurate colour measurements cannot be made if the observer is shading the viewed object or the colour chips with his/her body. Secondly, dappled sunlight as would be found under trees is similarly inappropriate. These authors propose that direct sunlight will allow for the most accurate measurements in comparison to the two preceding conditions. Taking this feature into account, it is proposed that a methodology for colour measurement be used that reflects how a soil scientist would describe colour in the field because that is predominantly where classification (and classification errors) take place. This is by no means an attempt to undermine the science behind colour interpretation, but rather an attempt to satisfy both sides of the spectrum – the proposed guidelines for accurate scientific interpretation of soil colour and the practical in-field plausibility of the

prescribed measurement method. In conclusion, using more than one person (minimum of 3) for colour interpretation, standardising the preparation of the soil for colour measurement (both undisturbed clods and crushed soil in a dry and moist state), utilising the appropriate and specified Munsell viewing masks and aiming for colour measurement under direct sunlight conditions are the standardised method proposed to measure soil colour in the field by means of the Munsell soil colour book.

Regardless of the accuracy or precision of determining soil colour using the Munsell soil colour charts, Viscarra Rossel et al. (2006; 2009) makes an important observation in stating that due to the nature of the Munsell system and the resulting notation it generates, it is more appropriate for categorical qualifications of colour and less suitable for statistical or numerical analyses. This of course is a universal problem across many industries focussed on colour and therefore other ways in which to express the colour of an object more suitable to these needs has been developed and applied. Quantifying the different wavelengths of light that are absorbed or reflected from the surface of an object and therefore making use of its reflectance properties is common practice. On a level more complex than what can be measured simply using vision, the reflectance properties of a soil can be described by spectrophotometric curves which quantify spectral reflectance (%) for each wavelength of light. This is primarily measured using spectrophotometers. A number of studies making use of these instruments for soil colour determination has proven them to be both accurate and precise in this regard (Shields et al. 1966; Torrent et al. 1983; Post et al. 1993). Although variations in the accuracy, precision and data output properties of different types of these instruments exists (Torrent & Barron 1993), recent attention has been given to portable spectrophotometers particularly due to their mobile application. Barrett (2002) measured in situ soil colour in well-drained sandy soils by means of a handheld spectrophotometer and found a moderately strong correlation between instrument and visual measurements although the spectrophotometer proved to provide a higher degree of precision. Viscarra Rossel et al. (2009) used a portable near-visible infrared (vis-NIR) spectrophotometer and found these instruments generate estimates of soil colour that was also in fair agreement with what was visually measured. The attractiveness of using these spectrophotometers is that, unlike human interpretation, they are standardised instruments that consistently provide objective measurements of soil colour. Unfortunately, the present cost of attaining these instruments make in-field soil colour interpretation using handheld spectrophotometers by the average soil scientist an unlikely ideal to strive for in any classification system.

Other instruments that are also used to measure soil colour and reflectance include spectroradiometers (Baumgardner et al. 1985) and photoelectric tristimulus colorimeters (Torrent &

Barron 1993). The study by Rabenhorst & Parikh (2000) is an example of a study where a digital colorimeter was used for colour determination, whilst a spectroradiometer was used by Sánchez-Marañón et al. (2004) for the same purpose. Tristimulus colorimeters generate tristimulus values as defined by the Commission Internationale de l'Eclairage (CIE), a concept that will be dealt with later under soil colour quantification. However, these instruments are deemed to be precise and user-friendly but can be less accurate as shown by Torrent & Barron (1993) who recorded differences in tristimulus values generated by the instrument itself and those obtained from spectral reflectance data conversions. Spectroradiometers measure spectral radiance or irradiance across various spectral ranges and therefore are used to characterise the reflectance characteristics of an object. For more precise descriptions of the functionality and application of these individual instruments, spectroradiometers are discussed in more detail by Baumgardner et al. (1985) whilst information on spectrophotometers and colorimeters are obtained in Torrent & Barron (1993). These three main instrument types used for colour or spectral reflectance measurements are also described by Barrett (2002). Baumgardner et al. (1985), however, makes users aware that various instrumentation systems exist with which reflectance measurements can be made but to be able to utilise and compare measurements from these different systems, a clear understanding of the conditions under which the measurements were made need to exist.

In addition to instruments mentioned above, other methods that have been proposed and tested with the aim of enhancing the objectivity with which soil colour can be measured include colour interpretations of digital soil photographs (Van Huyssteen et al. 2006a, 2006b; Viscarra Rossel et al. 2009). Although results have been promising, further research is needed in this field to improve the accuracy of this method (Van Huyssteen et al. 2006a).

### ***1.6. The quantification of soil colour***

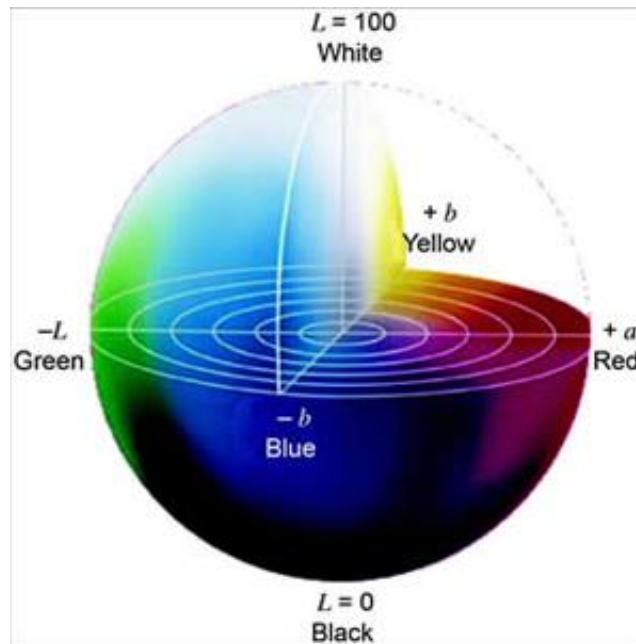
In order to relate soil colour to any measurable physical, chemical or mineralogical characteristic, colour has to be expressed in numerical units suitable for statistical analysis. A number of colour space models have been defined each quantifying colour using a specified unit. The application of these models for soil colour quantification differs however. A summary of all the colour space models applicable to soil colour as well as the methods for the transformation between the different models are given by Melville & Atkinson (1985) and Viscarra Rossel et al. (2006). The functionality of these colour space models is that they allow for individual soil colours to be represented in specified positions within a defined colour space. In addition to the Munsell soil colour system, the RGB, CIE XYZ, CIE Yxy, CIELUV and CIELAB systems are described by these authors. Based on their summaries, a short simplistic description of each follows:

- RGB: The RGB system is based on variations in the spectra of the three primary colours. Numeric tristimulus R G B values are generated that range from 0 to 255 for each primary colour - red (R), green (G) and blue (B). The defined colour space is represented by a three-dimensional cube, where individual colours can appear as points on or in the cube space.
- CIE XYZ: This system is generally the basis from which other colour specifications are made. Based on a standardised methodology defined by the CIE incorporating the spectral power distribution of a standard illuminating light source and the spectral response characteristics of the human eye, all colours can be described in terms of three variables X, Y and Z, known as the CIE XYZ tristimulus values (CIE 1931). Y represents the brightness of a colour, whilst X and Z are not physically realisable components. As a result of the nature of particularly the last two variables, it is difficult to visually represent single colours within this space model.
- CIE Yxy: To make visual representation easier, the CIE defined the CIE Yxy colour space (CIE 1931). This system makes use of the conversion of the XYZ tristimulus values to chromaticity coordinates x and y. Independent of Y, x represents a colour variation ranging from blue to red whilst y ranges from blue to green. As a result a colour can be represented through the combination of the x and y coordinates with the Y value within a two dimensional chromaticity diagram (Melville & Atkinson 1985). Unfortunately, as with the XYZ system, there are some discrepancies in the representation of perceived colour differences seeing that both these systems are non-linear.
- CIELUV & CIELAB (Figure 1.2): To better describe colour in a uniform colour space and with appropriate representation of perceived colour differences, the CIE developed the CIELu\*v\* and CIELa\*b\* systems (CIE 1978). CIELUV makes use of the transformation of the x and y chromaticity coordinates to a more uniform scale. The CIELAB values are generated through non-linear transformations of XYZ. In both systems, L represents luminance or brightness and ranges from black (0) to white (100); a\* and u\* represents a red (+)/green (-) scale; and b\* and v\* represents a yellow (+)/blue (-) scale. The representable model consists of a central y axis (Y) and two horizontal x and z axes (+a\*/u\* to -a\*/u\* & +b\*/v\* to -b\*/v\*) that are perpendicular to each other.

As mentioned, the functionality of these colour space models is that individual soil colours can be 1) visually represented in a defined space and 2) be transformed between the different units used in each following specified equations (Viscarra Rossel et al. 2006). Therefore, if the various instruments provide colour readings in different units, equations allow us to transform these units into other desirable colour spaces. This is probably most applicable where tristimulus values are generated by



the applied instrument and the resulting values can be transposed to Munsell hue, value and chroma (e.g. Torrent & Barron 1993 and Post et al. 1993) used in most soil classification systems.



**Figure 1.2.** A graphical representation of the CIE Lab colour space. Included with permission from [colorcodehex.com](http://colorcodehex.com) (<https://www.colorcodehex.com/color-model.html>).

What is noticeable, however, is that through point representation in a visually defined space the above mentioned models allow mostly for comparisons between the individual colours themselves (Melville & Atkinson, 1985). For the purpose of soil colour interpretation where the colour of a soil in its own sense has little significance, the main interest would be correlating soil colour to an additional colour-related variable indicative of a specific soil property or process. To put this in context, the main objective of this overall study can be used as an example. Topsoil bleaching is a discolouration phenomenon, for which not all the processes responsible for this morphological feature are known. Investigating all possible factors influencing this expression of colour requires a method with which soil colour can be related to soil properties or processes. The most simplistic solution to this predicament would be to use a single index value representative of soil colour that can be calculated from colour measurements and plotted against the numerical values of additional measurable soil properties in order to determine if a relationship exists. This concept has been applied in a number of studies where colour indices have been developed for soils with different colour characteristics. Examples of this include chroma or value indices (based on measurable Munsell chroma and value) used on soils displaying redoximorphic colour features (Rabenhorst & Parikh 2000) and anthraquic soils (Jien et al. 2004). Van Huyssteen et al. (1997) used indices incorporating dry soil colour hue, chroma and value to predict the duration of water saturation in a soil with reasonable accuracy.



In oxidic soils displaying diagnostic red colours, the development, application and adaptation of redness indices have been commonly used (Gobin et al. 2000). A variety of these redness indices, known as redness ratings (RR), were recorded and tested by Barron & Torrent (1986). The initial RR was proposed by Hurst (1977) and later modified by Torrent et al. (1980). It makes use of Munsell colour notation conversions. Both Munsell chroma (C) and value (V) as well as the variable H, which is the figure preceding the capital letters (e.g. YR) in the Munsell hue, are used. A second RR (defined as RI), making use of CIE chromaticity coordinates (Yxy) (Torrent et al. 1983), was also applied together with a third redness index based on the L, a\* and b\* values of the CIELAB colour system (Barron & Torrent 1986). Essentially these authors found that all the tested redness indices correlated well with the hematite content in the soil although saturation effects were recorded. Unfortunately, due to the dominant pigmenting effect of hematite, these indices do not allow for the accurate estimation of goethite in soil (Duiker et al. 2003).

From the above mentioned studies it can be concluded that the type of index that is used must be applicable to the colour characteristics and the processes responsible to the expression of colour in the particular soil. This implies that some knowledge needs to exist about the colour generating process as well as the dominant pigmenting influences in the soil. When there is variation in either or both of these factors, a single value index seems to be unsuccessful in describing the colour variations. For instance, when describing colour using a single index value for soils ranging from grey/bleached to red to yellow-brown in a sample set of 1440 soils, Carstens (2015, Thesis submitted) found that applying the Munsell based RR developed by Torrent et al. (1980) yielded unreliable results. As mentioned by Duiker et al. (2003), in the yellow-brown goethite dominated soils this index returned zero values which made comparisons between the soils impossible. It would seem that the different Fe oxide constituents and the variability in the degree to which they are expressed, makes the use of a single value index based on Munsell notation unfeasible under such circumstances.

The results from these colour index studies highlight the fact that colour is a complex feature and its complexity can in some part be attributed to its different dimensions. For example, a colour can be red or yellow but it can also be rich or dull or light and dark. The logical conclusion would then be that to be able to relate a single soil characteristic to a single numerical value, representative of soil colour, the dimension in which the soil property or process will cause the most colour variation should be the central component of such an index. This unfortunately is not as straight forward as it would seem, seeing that colour variation occurs across more than one dimension and to variable degrees, and is the result of a combined effect of the different soil pigmenting processes. Therefore, to actually be able to accurately quantify colour and relate it back to a specific soil property or process, one would

need to measure it in all its dimensions and rather not try to oversimplify this phenomenon. Especially in a scenario where no certainty exists about what factor is driving soil colour variation.

Although an emphasis has been put on soil colour quantification and the importance thereof for correlations to soil properties, the fundamental issue remains colour measurement. Although the Munsell system, which is most commonly applied in Soil Science, allows us to describe a colour in three dimensions, numerous problems associated with this mode of colour measurement have been described. The central issue, however, is that colour under these circumstances represent a sensory perception that varies under different circumstances. Nonetheless and as previously mentioned, it is the in-field application of the Munsell system as well as the relative simplicity with which colour can be measured in more than one dimensions that justifies its use. The problem therefore is how can soil properties be related to soil colour in a scientifically acceptable manner if visual measurement of colour is not standardised?

For fields of science that use sensory information, such as taste or colour, as measureable parameters, objective data collection and analysis is an important issue. Interpretation of sensory data is often used in food sciences (Bower 2006) where taste or smell needs to be assigned to a particular chemical component. Determining the physical and chemical properties of soils that influence soil colour have many parallels to the sensory studies of food science and a number of statistical tools used in food science are applicable to soil colour data analysis. In food science studies, expert tasting panels, trained in detecting certain characteristics, are used together with advanced statistical tools (e.g. PCA) in order to arrive at scientifically acceptable conclusions. An example of the use of Principal Component Analysis (PCA) in this context is provided in the study by Chapman et al. (2001). A summary of other applicable statistical methods are given by MacFie & Hedderley (1993).

### **1.7. Conclusions**

The colour of an object is probably the feature most commonly emphasized in its description although the spontaneous nature with which the human eye-brain system is able to register colour has meant that little attention is given to the recognition of this feature in everyday life. It is only after a more meticulous investigation into the science behind colour and a realisation of the numerous dimensions in which colour can vary, that the complexity of this phenomenon is comprehended. Within the field of soil science, colour as soil morphological feature has received considerable research attention. Beside the records of the various soil pigmenting agents responsible for the expression of colour in the solum, soil colour is of particular significance due to its relationship with soil properties, function and condition. It is also this relationship that provides the basis for soil colour's inclusion as diagnostic criterion in most soil classification systems of the world. Understanding and explaining the dynamics

of this association between colour and soil condition has been at the centre of most colour-related soil research. An essential component in all of these investigations is soil colour measurement and quantification. To be able to relate specific soil characteristics to the expression of a particular colour in a scientifically applicable manner, it is crucial that colour is objectively measured and appropriately quantified. Numerous colour space models, providing appropriate units with which soil colour variation can be quantified and described, have been developed and tested. Unfortunately, the need for a more practically applicable colour measuring protocol in the discipline of soil science has meant that colour measurement by means of visual estimation has been adopted as the standard. The sensory nature of colour detection through visual means results in subjective colour measurement. Therefore, even before colour is transposed into different units or colour space models, the fundamental colour-related issue in soil science remains colour measurement. If initial colour measurements are not standardised and accurate at least to some extent, wrongful conclusions about soil properties and function will result. In a study where colour is the only soil property indicative of an unknown pedogenetic process, it is undeniable that if soil colour is wrongfully determined no substantial relationship between soil function and colour will be observed, and when working with a small data set, this effect would be even more pronounced.

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## CHAPTER 2: SAMPLE COLLECTION AND ANALYSIS

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### 2.1. INTRODUCTION

Weakly structured, red and yellow soils are widely distributed across South Africa (Fey 2010). By implication, the widespread nature of these soils mean that they are present in climatic and geologically diverse parts of the country, a prime example being both the Western Cape and Mpumalanga Highveld. An investigation into the geomorphologic history of the Western Cape and the Mpumalanga Highveld, and the resulting similarities in the expressed morphology of some of the soils found in these two regions mean that soil from these locations provide the ideal substrate for comparative studies. Consequently, the bleaching of topsoils reported by Van der Waals (2013) on some of the weakly structured red and yellow subsoils of the Mpumalanga Highveld, together with the occurrence of similar soils exhibiting the same features in parts of the Western Cape, provided the rationale for using these two locations to study the bleaching of topsoils on weakly structured red and yellow subsoil horizons in South Africa.

#### 2.1.1. *Geology and geomorphology*

On the Mpumalanga Highveld, weakly structured oxidic soils dominate the landscape and form part of a red-yellow-grey catenal sequence that is commonly observed from Bronkhorstspuit west towards Belfast (Soil and Irrigation Research Institute 1987; Fey 2010). The geology of this region is diverse and comprises of shale, sandstone and occasional dolerite dikes primarily from the Transvaal and Karoo supergroups (Norman & Whitfield 2006). The landscape is extremely old and represents a lowered remnant of the African surface (approximate age: 65 million years) (Partridge et al., *Unpublished paper*). As a result of the warm and seasonally humid climatic conditions prevalent in this region, advanced chemical weathering of the existent parent materials has resulted in the development of deep, mature red and yellow apedal soils that are highly leached and also acidic.

In the Western Cape and particularly in and around Stellenbosch, weakly structured red and yellow soils are also present and represent some of the oldest soil materials in South Africa (Hendey 1983). In this region, these soils are mostly colluvial in nature and are predominantly found at the footslopes of the surrounding mountain ranges. Areas do however exist where these soils are present at higher altitudes where limited movement of soil materials has taken place. Distribution maps of these red and yellow soils indicate that their presence is restricted to an approximate altitude range of between 150 and 300 meters above sea level (Schloms et al. 1983). Compared to the rest of the soils in this region, these weakly structured red and yellow soils are observably different. To explain this apparent anomaly within the Western Cape soil landscape the unique geomorphological history of the area

provides the answers. According to Lambrechts (1983) many of the soils in the Western Cape are not in phase with their present environment. This implies that parent material, climate, topography and biotic factors have changed over the course of time, altering the soil forming processes with each such event. Lambrechts (1983) explains that the uniformly red- or yellow-coloured, dystrophic and apedal soils of this region originated as a result of weathering and soil formation in the early Cenozoic era. The warm humid climate that prevailed at this time was similar to tropical and subtropical conditions. This, together with the well-drained nature of the coastal forelands resulted in rapid chemical breakdown of primary silicates and consequently an abundance of kaolinitic clay and residual iron and aluminium oxides and hydroxides in the soil environment. Internal drainage and leaching further resulted in the almost complete loss of basic cations.

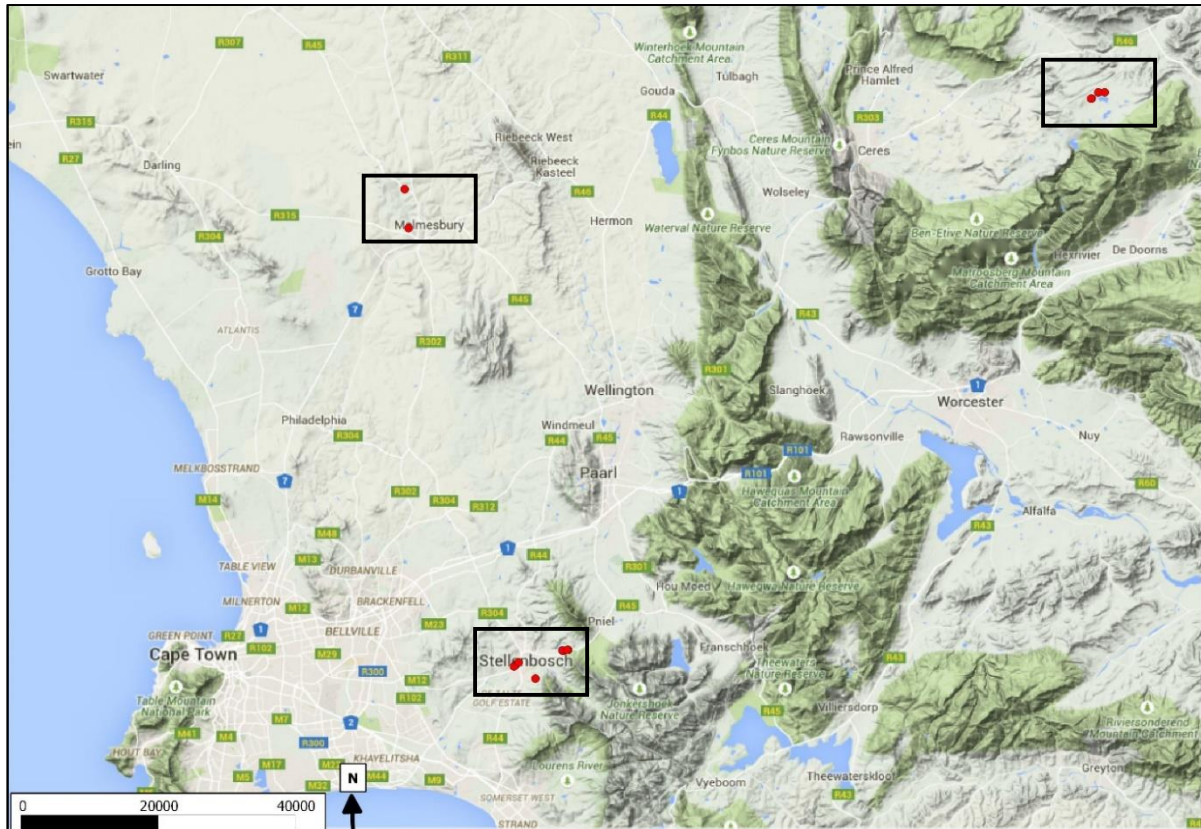
## **2.2. SAMPLING METHODS**

### **2.2.1. *Site and profile selection***

A total of 26 soil profiles were sampled across 9 different sites throughout the Western Cape and Mpumalanga provinces of South Africa. Fourteen profiles were selected in the Western Cape, the sites including areas in and around Stellenbosch (Papegaaiberg, Old Helshoogte pass and Welgevallen experimental farm), Ceres and Malmesbury (Figures 2.1 & 2.3). The climatic conditions in this part of the country is characterised by dry summers and wet winters, typical of a Mediterranean climate. The average rainfall in these regions is variable but for the largest part exceeds 500 mm per year (Oberholzer & Schloms 2010). The mean annual maximum and minimum temperatures are also regionally different, although Malmesbury, Stellenbosch and Ceres reach daily maximum temperatures easily surpassing 30°C in the dry summer months, with the latter two locations also frequently experiencing snow on the nearby mountain ranges during winter.

The soil profiles chosen for this study in the Western Cape needed to represent profiles that could potentially qualify as having red/yellow-brown apedal B horizons or red/yellow neocutanic B horizons. Within the South African soil classification system these diagnostic horizons are all defined based on a poorly developed structure, with the distinguishing feature being the type and degree of colour expression in the soil matrix (Soil classification working group 1991). One of the profiles chosen, (W3, Welgevallen experimental farm, Stellenbosch) (Figure 2.3a) was the subject of much debate during the soil excursion at the 2009 Combined congress held at Stellenbosch University. At this profile many of the delegates argued that the profile should be classified as a Hutton (Orthic A - red apedal B - unspecified), whilst others preferred the profile to be classified as a red Oakleaf (Orthic A - neocutanic B - unspecified) due to the bleached topsoil. The controversy around this profile meant that W3 represented the type of profile that had to be targeted in this study. Profiles similar to W3 having bleached and non-bleached topsoils were thus selected for the study. Samples were collected from

profile pits or well excavated road cuttings and most of the selected profiles had weakly structured red subsoils, with yellow variants being less common. All Western Cape profiles were undisturbed prior to sampling.

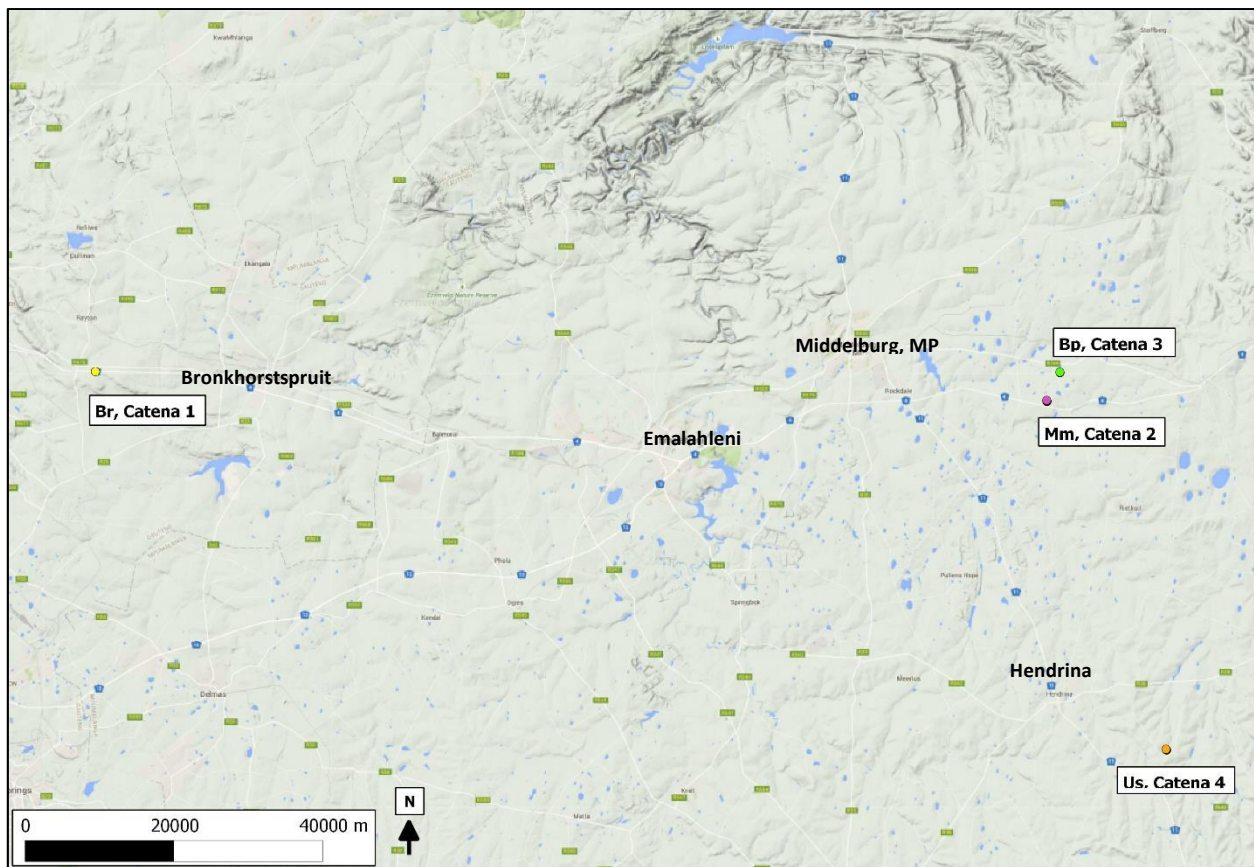


**Figure 2.1.** The sites and positions of the soil profiles sampled across the Western Cape.

In Mpumalanga, a total of 12 profiles were selected across the eastern part of the Highveld (Figure 2.2). In contrast to the selected sites around the Western Cape, the areas from which soils were sampled on the Highveld experiences summer rainfall although maximum temperatures similarly also exceed 30°C. The daily and seasonal fluctuation between maximum and minimum temperature is also more extreme in this region. The selected sites ranged from the University of Pretoria's experimental farm near Bronkhorstspuit to cultivated lands around the Middelburg and Hendrina area (Figure 2.2). The Bronkhorstspuit profiles were located on uncultivated land. However, it was not possible to find undisturbed sites with apedal soils around Middelburg and Hendrina thus these profiles were all sampled in maize fields during the fallow season (July 2014) prior to any seasonal ameliorants being added to the soil. Similar to the Western Cape however, the profiles also consisted of bleached and non-bleached orthic A horizons overlying either red apedal B, yellow-brown apedal B or neocutanic B subsoil horizons. Plinthic horizons also occur at depth in many of these soil profiles, which is characteristic of the area (Fey 2010). Typically, the soils of the Highveld region follows a catenal sequence which in its perfect form is represented by red soils on well-drained crests grading through

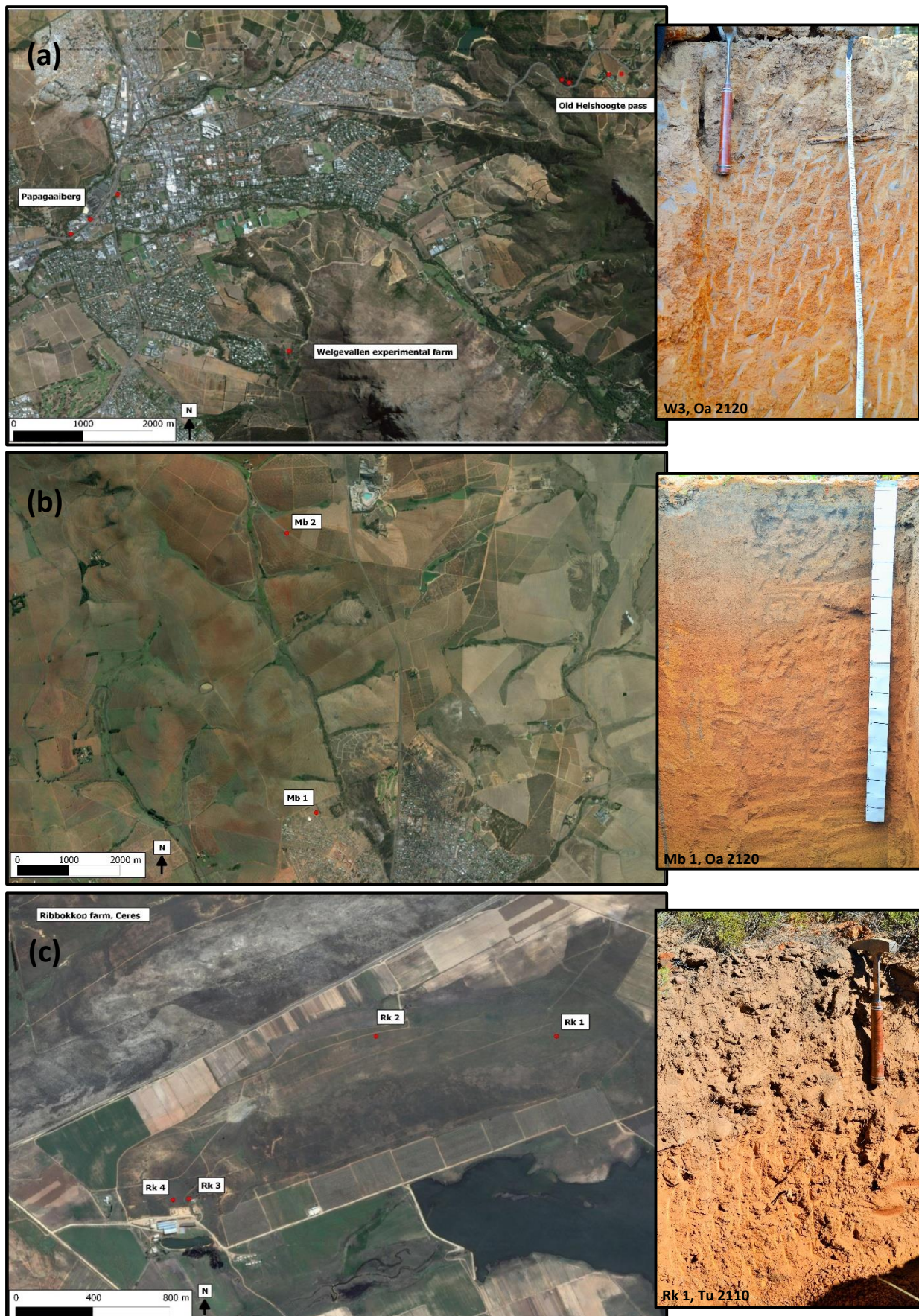


yellow soils on midslope positions towards gleyed colours in the poorly-drained footslopes and valley bottoms (Soil and Irrigation Research Institute 1987; Fey 2010). It is on these catenal sequences that bleaching tendencies were reported by van der Waals (2013), and thus soils were largely collected along catenal transects. The toposequences were initially identified by augering holes every 10 meters. Profile pits were dug at representative positions along transects and samples were collected from these pits. Additional auger samples of the top two horizons were collected in between the profiles pits in order to obtain a better understanding of soil colour variation along the Highveld catenas. A total of four catenas were sampled (Figures 2.4 – 2.7).



**Figure 2.2.** The locations of the soil profiles and plinthic catenas sampled across the Mpumalanga Highveld. The catena numbers and sample names are indicated on the map.



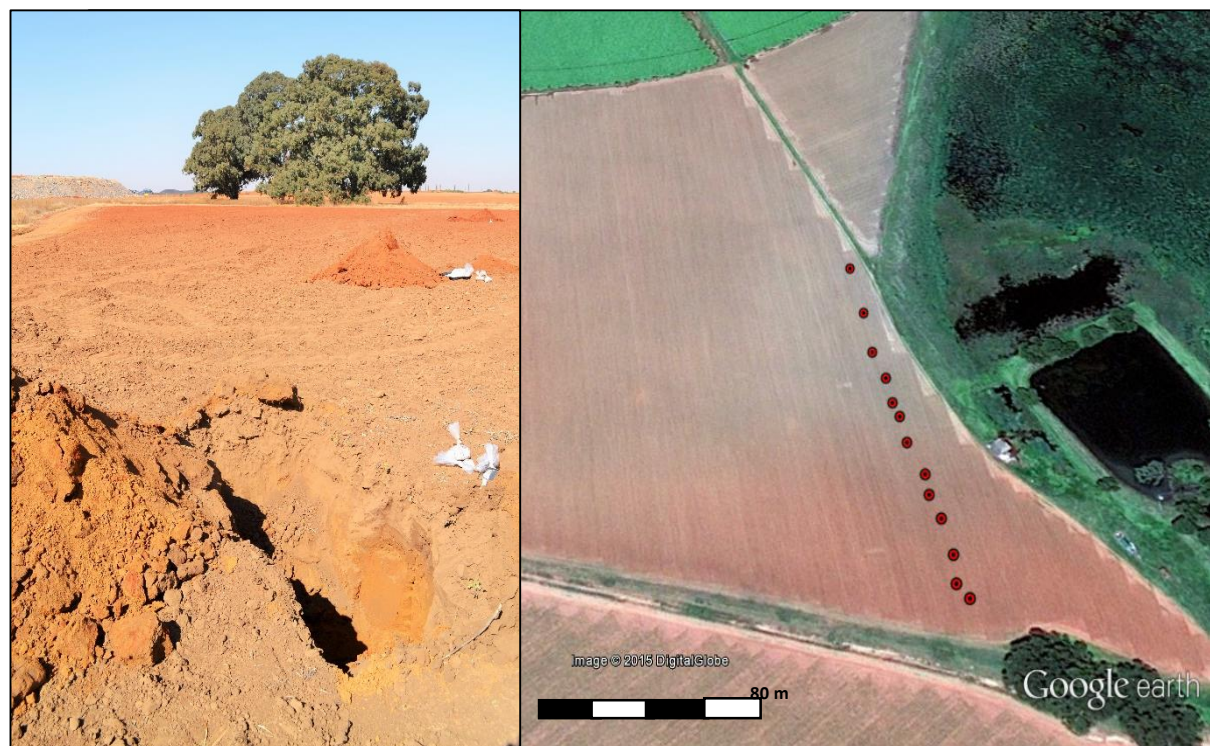


**Figure 2.3.** Satellite images and photographs of the sites and some representative profiles sampled in the Stellenbosch (a), Malmesbury (b) and Ceres (c) regions of the Western Cape.



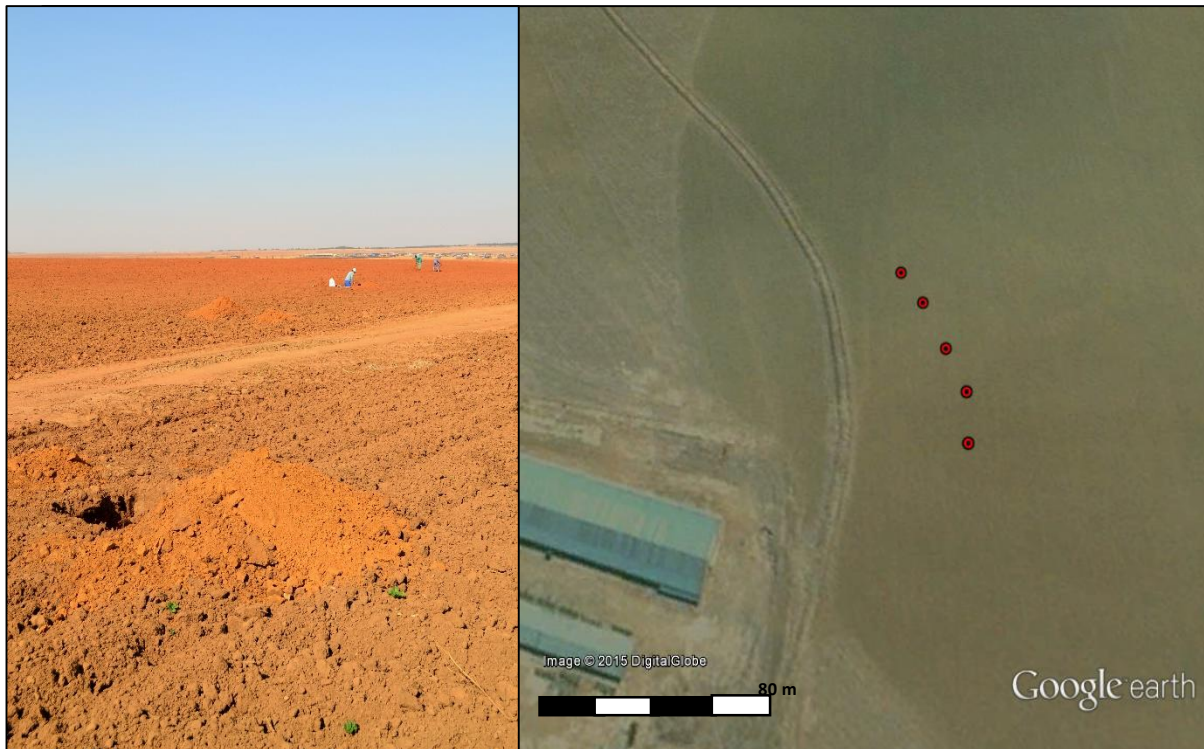


**Figure 2.4.** Catena 1. Satellite imagery and a photograph of Catena 1 on the University of Pretoria's experimental farm next to the N4 near Bronkhorstspuit. In the bottom left of the photograph the first profile pit can be observed, with the second being a mere 15 m away at the point indicated.



**Figure 2.5.** Catena 2. Satellite imagery and a photograph of Catena 2 on the farm Beestepan near Middelburg, MP. Auger samples were collected at each position along the catena.





**Figure 2.6.** Catena 3. Satellite imagery and a photograph of Catena 3 on the farm Beestepan near Middelburg, MP. Auger samples were collected at each position along the catena.



**Figure 2.7.** Catena 4. Satellite imagery and a photograph of Catena 4 on the farm Uys near Hendrina, MP. Auger samples were collected at each position along the catena.

### **2.2.2. Soil sampling and preparation**

All soil profiles were photographed and described using the detailed procedure prescribed by the ARC-institute for Soil, Climate and Water (Turner 1991). For every profile soil samples were collected from both A and B1 horizons by taking a representative sample of the entire horizon throughout its depth, placing it in a sample bag and labelling it. At some of the Mpumalanga sites, transition zones (A/B) were also sampled as additional horizons when it was deemed necessary.

In addition to sampling profile pits on the Mpumalanga Highveld, auger samples were also collected along the catenal transects up to a depth of approximately 1 – 1.2 m at distances 10 to 20 m apart. An A and B1 horizons were collected as well as an A/B transition zone in some instances. The number of auger samples varied with each of the catenas, catena 1 having the least number of samples (2) and catena 2 having the most (13) (Figure 2.2). Samples collected from the auger holes were only analysed for colour and total Fe content.

Sample preparation entailed the drying and sieving of the collected soil samples. Soils were spread out in a temperature-controlled room (set at approximately 25°C) and left for a two-day period. Following drying, the entire sample was weighed and sieved through a 2 mm sieve. The separated soil fraction (<2 mm) was transferred to labelled sample boxes and the non-soil fraction (>2 mm) was weighed to determine the coarse fragment percentage of the soil. Soil physical and chemical characteristics were determined on the dried and sieved soil samples.

### **2.2.3. Soil colour determination**

In-field soil colour measurements were conducted using a Munsell soil colour chart (Munsell Color Company 1975) and entailed determining the colour of the soil in a dry and moist state in both the soil's natural state of aggregation i.e. as clods and as fine sample. Lighting conditions were kept relatively constant by measuring the soil colours in direct sunlight and using the appropriate colour masks (as specified by the Munsell soil colour chart). More than one observer was also used to limit subjectivity. Notes were made whenever there were inconsistencies in the colour measuring conditions and these colours were re-measured back at the laboratory under simulated field conditions. Random samples were also selected from the collected soils following field work and their colours were re-measured in the lab to ensure accuracy.

Following sample collection and in-field soil colour measurement, the sampled soils were taken back to the laboratory for colour measurement by means of a Konica Minolta CM-600d spectrophotometer (Minolta, Osaka, Japan). The spectrophotometer first had to be set up for this particular purpose. This entailed measuring each of the colour chips from a new Munsell soil colour chart in  $L^*a^*b^*$  units (CIELAB colour space model, Figure 1.2) with the instrument and specifying ranges of these values as

target colours. This would allow for individual soil colours to be related back to reference Munsell target colours based on the  $L^*a^*b^*$  values measured by the instrument. Therefore, in addition to  $L^*a^*b^*$  units, the instrument was set up to be able to assign every individual sample with a Munsell *hue*, *value* and *chroma*. No numerical conversions from  $L^*a^*b^*$  to Munsell *hue*, *value* and *chroma* were used in this study. The tolerance settings for the upper and lower limit of target detection was 0.8 to -0.8 respectively. The instrument was set on auto target selection mode and the selection range was specified at a defined euclidean distance ( $\Delta E_{ab}$ ) of six units. Standard D65 lighting conditions were selected and the observer settings was specified at 10 degrees. Measurements were taken with the SCI-setting (spectral component included) activated.

After the instrumental setup was completed, the dry fine soils were individually spread out on a flat surface and covered with a pure light glass lens (Konica Minolta CM-A212 Calibration Glass Ø 45mm; A168-716). The spectrophotometer was then aligned over the surface of the glass lens and a reading was taken. The glass lens was removed and following measurements in the dry state, the sample was moistened with a fine spray water bottle and another spectrophotometer reading was made in the moist state. Following each measurement, the glass lens was cleaned with a fine-fibred cloth to prevent scratching or any form of damage that could influence the colour reading.

The specified colour measurement protocol was applied to both the profile- and catena samples that were collected during the study.

## 2.3. PHYSICAL AND CHEMICAL CHARACTERISATION METHODS

### 2.3.1. *Physical soil parameters*

#### 2.3.1.1. *Particle-size analysis*

For particle size analysis the samples were pre-treated by removing organic matter and Fe oxides using hydrogen peroxide and citrate-bicarbonate-dithionite, respectively, as specified by Gee & Bauder (1986). Thereafter the treated samples were chemically dispersed by adding Calgon dispersing agent (Na-hexametaphosphate mixed with  $\text{Na}_2\text{CO}_3$ ) and transferring the suspension to a dispersion cup where it was mixed with an electric mixer for 5 minutes (Soil classification working group 1991). The dispersed sample was then washed through a 270 mesh sieve (0.053 mm) to separate the silt and clay fraction from the sand fraction. The sand fraction was dried and transferred to a nest of sieves arranged in decreasing size from 1.0 mm, 0.5 mm, 0.25 mm, 0.106 mm and 0.053 mm, with a pan at the bottom to collect any additional silt and clay fractions. The sieves were shaken for 10 minutes on a sieve shaker to separate the individual sand fractions. The additional clay and silt fraction collected in the pan was added to the dispersed silt and clay and the suspension was transferred to plastic

bottles. A representative subsample from each of the suspended silt and clay volumes were analysed using a Micromeritics Saturn DigiSizer 5200 high definition digital particle size analyser (Micromeritics, USA) in order to identify both the fine and coarse silt and clay fractions. The size fractions for coarse silt (including medium silt, 0.02-0.05 mm), fine silt (0.002-0.020 mm), coarse clay (0.0002-0.002 mm) and fine clay (<0.0002 mm) defined by Gee & Bauder (1986) were used. All the soil fractions were expressed as mass percentages following the calculations specified by the Soil classification working group (1991).

#### *2.3.1.2. Bulk density*

The bulk density of each soil horizon was determined from undisturbed clods collected during profile sampling, following the standard clod method described by Blake & Hartge (1986). The water-repellent substance used to cover the clods was a low melt-point paraffin wax (density: 0.9 g.cm<sup>-3</sup>). Bulk density was determined following the calculations specified in the method.

#### *2.3.1.3. Water dispersible clay*

Water dispersible clay was determined following the method proposed by Seta & Karathanasis (1996). Equipment restrictions meant that only 50 ml of liquid could be added to smaller soil samples of 2.5 g in 50 ml centrifuge tubes. In addition, all samples were centrifuged at 800 rpm for 3.5 minutes. As specified by the method, dispersible clay was first gravimetrically determined for each sample in deionized water (WDC) and thereafter using a sodium dispersing agent (SDC). Calgon dispersing agent (Na-hexametaphosphate mixed with Na<sub>2</sub>CO<sub>3</sub>, pH 9.0 - 9.5) was used and not pure Na<sub>2</sub>CO<sub>3</sub> (pH 9.5) as described by these authors. Due to the small soil sample sizes, weights were determined using a five decimal scale and all extractions were done in duplicate. The determined weights were expressed as a fraction of the total clay content and based on the average of the duplicate measurements, both a water dispersible clay (WDC) and sodium dispersible clay (SDC) phase was determined for each sample. The WDC % was then calculated by expressing WDC as a percentage of SDC to estimate the dispersibility of the clay phase in water.

### **2.3.2. Chemical soil parameters**

#### *2.3.2.1. pH and Electrical conductivity (EC)*

Soil pH was measured in a 1:2.5 soil solution using both distilled water and 1 M KCl following the standard procedures prescribed by Rowell (1994). Samples were shaken on an industrial shaking machine for 15 minutes and measurements were taken with a Eutech pH 700 pH meter by inserting the electrode into the soil suspension and swirling the suspension over the electrode. The pH value was only recorded after the reading stabilised.



In addition, all the sampled profiles were also subject to pH measurements in 1 M NaF. The  $\text{pH}_{\text{NaF}}$  was measured to detect any podzolic characteristics in the samples following the method used by Fieldes & Perrott (1966). A soil solution of 1:50 was used and pH was determined with a Eutech pH 700 pH meter after 60 minutes following intermittent shaking.

Electrical conductivity (EC) was measured on the samples prepared for pH determination in water (1:2.5 soil to water ratio) with a Jenway 4510 conductivity meter. The findings of Sonmez et al. (2008) concluded that extracts of either 1:1, 1:2.5 and 1:5 soil to water ratios can be used to estimate electrical conductivity and the ion concentrations of soils.

#### 2.3.2.2. *Exchangeable basic cations and exchangeable acidity*

Based on the recommendations of Isbell (2002) regarding the calculation of the exchangeable sodium percentage (ESP) in acidic soils (pH around 5.5), ECEC rather than the CEC at pH 7 was determined. The ammonium acetate method was used following the centrifuge procedure as described by Thomas (1982). All samples were centrifuged at 4000 rpm for 10 minutes. Even at a higher rpm than specified in the method, no clear decant could be obtained and the solution was passed through Whatman No 2 filter paper in plastic funnels. The collected filtrate was then sent for cation determination using Atomic Absorption Spectroscopy (AAS).

Exchangeable acidity was determined through means of titration using 1 M KCl as the replacing solution as specified by Thomas (1982). No Büchner funnels were used as prescribed by the method but rather a centrifuge procedure similar to the method described above for the determination of exchangeable basic cations. Soil (10 g) was placed into a 50 ml centrifuge tube and 6 increments of 25 ml of 1 M KCl was added. After each addition of KCl the solution was shaken by hand and left to stand for 30 minutes. Thereafter the sample was centrifuged at 5000 rpm for 5 minutes and the decant was passed through plastic funnels fitted with Whatman No. 2 filter paper. This procedure was repeated without changing the soil in the centrifuge tube. Phenolphthalein was added to the filtrate, which was titrated with 1 M NaOH to the first permanent pink endpoint to determine KCl acidity. To estimate the amounts of  $\text{Al}^{3+}$  and  $\text{H}^+$ , 10 ml of 1 M KF was added and the solution was titrated with 0.1 M HCl until the pink colour disappeared. Both the NaOH and HCl titer was recorded and the calculations specified in the method were used to determine both exchangeable acidity and exchangeable Al.

Various standard cation ratios and percentages were calculated with the obtained data. Effective cation exchange capacity (ECEC) was determined as the sum of the exchangeable basic cations and exchangeable acidity, ESP was calculated by expressing the exchangeable  $\text{Na}^+$  as a percentage of the ECEC and a Ca:Mg ratio was also determined (Isbell 2002).

#### 2.3.2.3. *Citrate bicarbonate dithionite (CBD) extractable Fe and Al*

CBD extractable Fe and Al was determined following the standard procedure developed by Mehra & Jackson (1960). Soil samples were, however, not ground to pass a 100 mesh sieve as specified. A number of the soil profiles contained small (<2 mm) transported ferruginised shale fragments that are not pedogenically linked to the soil. It was assumed that milling would overestimate the crystalline Fe content of these soils. This was verified by taking a subsample of 5 soils across both locations and comparing the difference between extractable Fe in milled (ball mill, 3 minutes) and unmilled samples. Some replicates of the milled and unmilled samples were also included. The results indicated that milling increased the CBD extractable Fe in the soils containing ferruginised rock fragments, while milling had very little effect on the CBD Fe of the other soils (Appendix 2.1). Therefore, to minimise the influence of such fragments in the CBD Fe measurements, unground (<2 mm) soils were used for the extractions. Following the extraction process, Fe and Al content was determined using AAS and the detected concentrations were expressed as a mass percentage of the soil.

#### 2.3.2.4. *Acid ammonium oxalate extractable Fe and Al*

Acid ammonium oxalate (AAO) extraction in darkness was used to extract poorly crystalline Fe and Al phases following the method prescribed by Loeppert & Inskeep (1996). The ferruginised rock fragments contained highly crystalline Fe therefore milling would have no influence on amorphous Fe extraction thus all samples were ball-milled for three minutes until ground to pass a 100 mesh sieve. The low quantities of poorly crystalline Fe and Al that generally occur in soils was the main motivation for milling samples in accordance to the standard method. Following the extraction process, Fe and Al content was determined using AAS and the detected concentrations were expressed as a mass percentage of the soil.

A Fe crystallinity index (CI) was calculated expressing AAO extractable Fe (poorly crystalline Fe) as a percentage of CBD extractable Fe (crystalline and poorly crystalline Fe). This was used to quantify the degree of crystallinity of the Fe phase. This was repeated for extracted Al.

#### 2.3.2.5. *Total carbon and nitrogen*

The carbon and nitrogen content of each sample was determined through the dry combustion method as discussed by Nelson & Sommers (1996) using an Eurovector elemental analyser. Soil samples were ground for three minutes using a ball-mill where after 2-5 mg of the milled sample was placed in a tin sample cup, crimped to confine it and introduced into the quartz reactor of the instrument. From the obtained results a C: N ratio was determined.

### **2.3.3. Additional soil parameters**

#### *2.3.3.1. Total Fe (Catena samples)*

The auger samples collected along the catenal transects on the Mpumalanga Highveld were analysed for total Fe content by means of a handheld Thermo Scientific Niton XL3t GOLDD+ XRF instrument. Prior to the measurements, both the top- and subsoil auger samples were ball-milled to create a more uniform sample structure for x-rays to penetrate. Iron content was expressed as a mass percentage.

#### *2.3.3.2. Clay mineralogy*

Clay separation for XRD analysis was done based on the methods proposed by Harris & White (2008). Clay mineralogy was only determined for four of the sampled soils (Pb 3.1, Pb 3.2, Hh 4.1, Hh 4.2), but for each Mg- and K-saturated samples were prepared. Sample pre-treatment did not entail the removal of any cementing agents and the clay fraction was dispersed using Calgon. The dispersed clay fraction was decanted and flocculated through the addition of 1 M HCl. The flocculated clay fraction was split and cation saturation was accomplished by making up approximate solutions of 0.5 M  $\text{MgCl}_2$  and 1 M KCl respectively using the clay suspensions. The K- and Mg- clay slurries were shaken by hand and centrifuged at 1000 rpm for 3.5 minutes to dewater the samples. Each sample was washed again using 0.5 M  $\text{MgCl}_2$  and KCl solutions and thereafter excess salt was removed by washing the samples with a 1:1 methanol-water solution. The concentrated clay fraction was transferred to dialyses tubing and placed in a water bath until the water bath tested free of chlorides. The dialysed clay samples were air dried and ground by hand using a mortar and pestle. The prepared samples were sent to iThemba Laboratories in Cape Town for XRD analysis at angles ranging from 4 to 60 degrees.



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## CHAPTER 3: SOIL-COLOUR RELATIONSHIPS

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### 3.1 INTRODUCTION

The inclusion of soil colour as horizon criteria in many soil classification systems (Soil classification working group 1991; IUSS working group WRB 2007; Soil survey staff 2010) is the result of its reported significance as a morphological feature indicative of soil properties, function and condition (Van Huyssteen & Ellis 1997; Rabenhorst & Parikh 2000; He et al. 2003; Sánchez-Marañón et al. 2004). Colour has been a central topic in many soil research ventures but despite its seemingly well-researched nature, colour expression in the soil solum remains a somewhat complex phenomenon to which soil scientists are often complacent. From the literature reviewed in Chapter 1 it was concluded that the complexity of soil colour originates from the multiple dimensions in which colour can show variation, the continuous nature with which colour is expressed in the soil, and the contribution of different soil features and conditions towards displayed colour. To those interested in confining soil colour to any discrete measurement unit and to further investigate what soil properties are responsible for the specific expression of colour under certain conditions, these above mentioned aspects pose significant challenges.

In the context of this study where the selected soils are all defined to some extent based on their expressed colour, and even more importantly, where bleaching as a discolouration phenomenon is assumed to be indicative of some or other pedogenetic process, being able to accurately measure colour whilst simultaneously being able to relate it back to specific soil properties are fundamental to the overall objectives of this research. Therefore, in order to investigate soil-colour relationships in this particular suite of soils, attention must be given to i) the applied colour measurement protocol and the generated colour variables in each, as well as ii) the influence of chemical and physical soil characteristics on colour expression.

Melville & Atkinson (1985) warns that any error in soil colour measurement may result in wrongful conclusions about profile characteristics. Therefore it was deemed that an investigation into the methods of colour measurement in order to see how colour measurement procedures can potentially influence determined colour should precede any actions aimed at relating colour to specific soil properties. As stipulated in Chapter 1, the measurement of soil colour can be objectively achieved using a calibrated instrument (Barrett 2002) although visual colour assessment is the procedure most commonly used by the soil scientist during soil classification in the field. As a result, visual colour measurement is essential to include in the current study as a prominent measurement technique. Furthermore, soil colour is measured using Munsell colour charts, thus comparisons need to be made

using this colour space model. The first aim of this chapter will be to determine how visual colour assessment compares with spectroscopic colour measurement in the Munsell colour space. The influence of the addition of moisture on soil colour using both these measurement techniques will also be assessed and colour measurements in the CIELAB colour space will also be carried out for comparison sake.

Within the context of the overall study, bleaching as a colour-related soil phenomenon is investigated and the particular interest is what pedogenetic mechanism is causing this expression of colour in the soil. It seems inconceivable that such objectives will be reached without an adequate understanding of the relationship between soil properties and the ensuing colours expressed in the soil solum. Therefore, in addition to investigating the methods of soil colour measurements, the second and final aim of this chapter is to determine what soil properties are responsible for colour expression in the sampled weakly structured soils of the Western Cape and Mpumalanga Highveld.

## 3.2 MATERIALS AND METHODS

Soil sampling, colour measurement and physical and chemical soil characterisation was completed following the methods specified in Chapter 2.

### 3.2.1 *Statistical analyses*

For each soil sample, Munsell *hue*, *value* and *chroma* as well as  $L^*$ ,  $a^*$  and  $b^*$  values were recorded under dry and moist soil conditions. To investigate the relationship between the colours determined through visual perception (perceived) and spectrophotometer measurements (measured), Spearman-r correlation coefficients were calculated for each colour variable between these two measurement conditions. The same technique was applied to dry and moist colour variables to determine whether i) the changes in colour brought about by the addition of moisture followed a consistent pattern, and ii) to see whether the values registered by the instrument and human vision in this regard were similar.

Spearman-r correlation coefficients were reported throughout the study due to this coefficient's ability to compensate for outliers. This implies that Spearman-r values provide an accurate representation of the correlation between variables in both normally and not-normally distributed datasets.

To determine the nature and the magnitude of the colour change between visual perception and instrument measurements, the difference between perceived and measured colour variables were calculated. The same technique was also applied to dry and moist colour and a series of One-way ANOVAs were completed for each of the Munsell colour variables to determine if the extent of the

colour change brought about by the addition of moisture were similarly registered between measured and perceived means. Due to the nature of the Munsell *hue* variable being a combination of both a number and letters, a linear scale with substituted numerical values were used. The substituted values included 2.5YR = 2.5, 5YR = 5, 7.5YR = 7.5 and 10YR = 10. In the case of the L\*, a\* and b\* values, no comparison could be made between perceived and measured colours and therefore only the influence of moisture could be investigated. For each of these CIELAB colour variables, One-way ANOVAs were completed to determine how and whether the values measured in the moist state differed from those of dry soil samples.

A Multiple Factor Analysis (MFA) incorporating the determined soil parameters and the related colour variables was conducted to investigate the relationship that exists between the recorded soil properties and the expressed soil colours. A Spearman-r correlation matrix making use of these same variables was also generated to explain the findings. In addition, separate correlation matrices reporting on the relationships between the i) determined soil colour variables and also ii) the determined physical and chemical soil parameters were also completed.

All statistical analyses was completed using Statistica 12 (StatSoft, Southern Africa).

### 3.3 RESULTS AND DISCUSSION

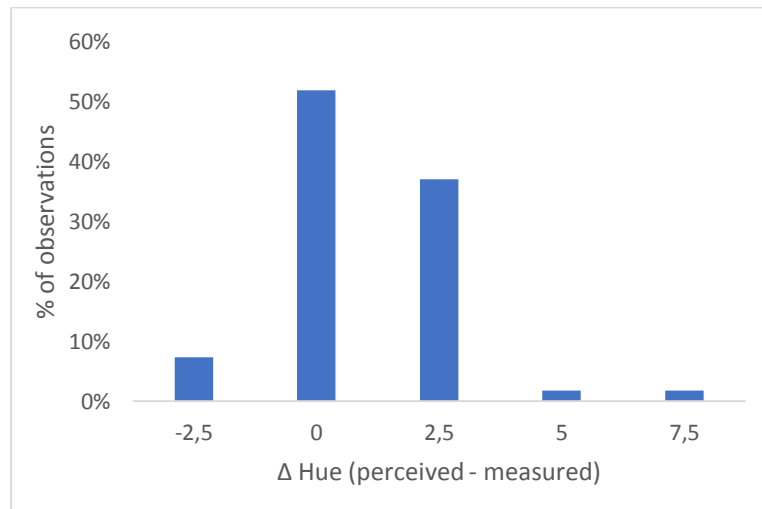
#### 3.3.1 *Colour measurement condition: perceived vs measured colour*

Colour has different dimensions of variation. For example, a colour can be red or yellow but it can also be rich or dull or light and dark. Therefore, to be able to encapsulate and accurately quantify this phenomenon, colour space models with multiple dimensions have been developed (Viscarra Rossel et al. 2006). The Munsell colour space model for example describes a colour based on its primary hue (an indication of a colour's relation to red, yellow, green, blue or purple), the richness of this hue (chroma) and the lightness of the overall colour (value) (Munsell Color Company 1980). As stipulated in Chapter 1, each of the developed colour space models makes use of different dimensions for colour quantification and therefore the colour variables generated in the Munsell and CIELAB colour space models will overlap to some extent, but will not be completely similar. Based on this premise, it was decided that to be able to evaluate colour measurement and colour description under different conditions, these different colour dimensions or variables would need to be individually assessed. In order to satisfy the first objective of this study, separate Spearman-r correlation matrices were generated for each variable in the Munsell colour space (Table 3.1) under different colour measurement and soil conditions to provide an indication of the variation caused by each of these factors.

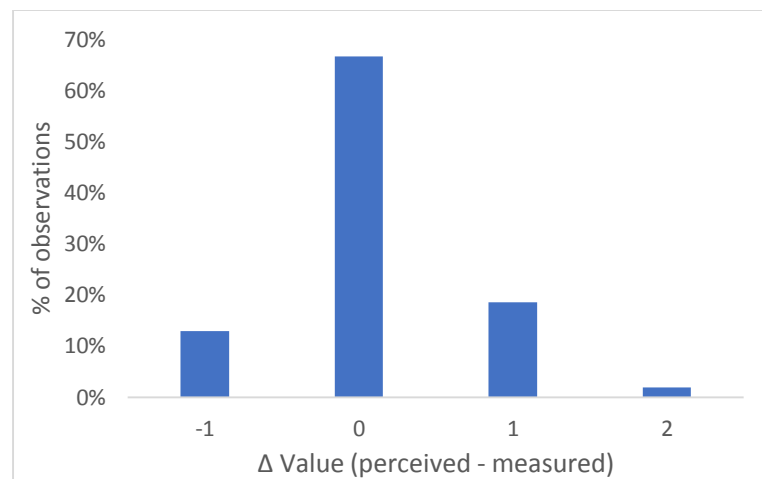
**Table 3.1.** The generated Spearman-r correlation matrixes for each colour variable in the Munsell colour space model under different measurement and soil conditions.

	Hue (perceived, dry)	Hue (perceived, moist)	Hue (measured, dry)	Hue (measured, moist)
Hue (perceived, dry)	1	0.86	0.54	0.37
Hue (perceived, moist)		1	0.59	0.41
Hue (measured, dry)			1	0.51
Hue (measured, moist)				1
	Value (perceived, dry)	Value (perceived, moist)	Value (measured, dry)	Value (measured, moist)
Value (perceived, dry)	1	0.44	0.60	0.10
Value (perceived, moist)		1	0.43	-0.12
Value (measured, dry)			1	-0.15
Value (measured, moist)				1
	Chroma (Perceived, dry)	Chroma (Perceived, moist)	Chroma (measured, dry)	Chroma (measured, moist)
Chroma (Perceived, dry)	1	0.70	0.49	-0.17
Chroma (Perceived, moist)		1	-0.17	-0.11
Chroma (measured, dry)			1	-0.09
Chroma (measured, moist)				1

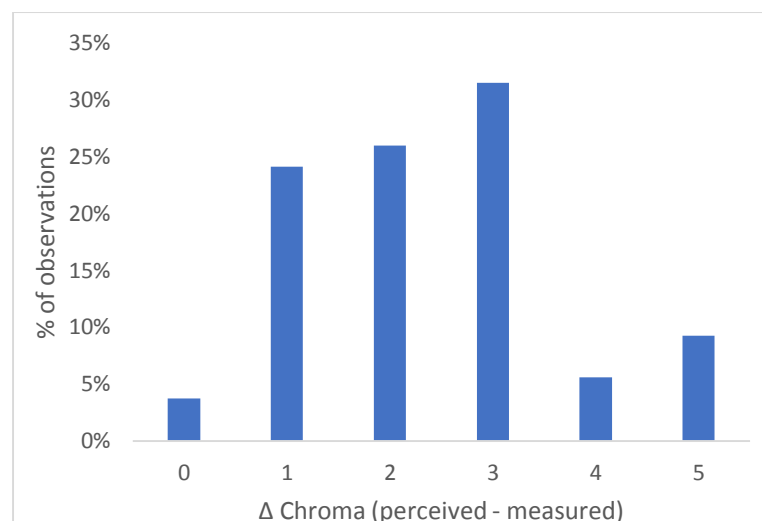
From the correlation coefficients provided in Table 3.1, it is apparent that visual (perceived) and spectroscopic colour (measured) determination registers changes in *hue*, *value* and *chroma* in a consistent manner when the soil is in a dry state. Perceived and measured Munsell *value* in particular revealed a significant positive correlation ( $r=0.60$ ) whilst perceived and measured *chroma* proved to be the least correlated ( $r=0.49$ ). Perceived and measured *hue* exhibited a correlation of  $r=0.54$ . Unfortunately, the results presented in Table 3.1 only provides information on the relationships which exist between measured and perceived (and dry and moist) colour variables without any reference of the magnitude of change under different measurement- and soil conditions and essentially to what extent the colour variables actually differed. Due to the variation in the colour of the soils sampled as part of this study (Chapter 2), the difference between each colour variable from one measurement technique and/or soil condition to the next was used in the subsequent statistical analysis rather than the absolute colour values of the soil samples. Therefore, the difference between the colour components measured under different conditions was calculated for each soil (e.g. perceived *hue* – measured *hue*) and the frequency of the residuals were graphically displayed in the form of histograms (Figure 3.1 a-c). Figure 3.1 indicates the percentage of the total number of observations per residual unit. For each soil the difference in *hue* (Figure 3.1a), *value* (Figure 3.1b) and *chroma* (Figure 3.1c) between perceived and measured values were determined and the frequency per delta unit was calculated and expressed as a percentage of the total number of observations. If the difference between perceived and measured colour variables equals zero this implies that no difference existed between visual and spectroscopic colour determination for that specific variable.



(a)



(b)



(c)

**Figure 3.1.** The percentage of the total number of observations per unit difference between perceived and measured hue (a), value (b) and chroma (c).

In Figure 3.1a it can be observed that the majority of *hues* visually determined corresponded to those measured with the instrument ( $\Delta \text{hue } 0 = 52\%$ ), although the higher percentage of observations for  $\Delta \text{hue}$  unit 2.5 (37%) indicate that the spectrophotometer tended to occasionally register lower and therefore slightly redder *hues*. Munsell *value*, however, was the colour variable that most frequently agreed between perceived and measured colours ( $\Delta \text{value } 0 = 67\%$ ; Figure 3.1b). The most variability was reported in *chroma* where Figure 3.1c clearly show that perceived and measured *chromas* rarely matched ( $\Delta \text{chroma } 0 = 4\%$ ), with the instrument consistently registering a lower *chroma* than what was visually perceived. Overall the eye perceived the soils to be brighter and more chromatic and was consequently less sensitive towards detecting bleached horizon colours. These reported discrepancies between measured and perceived colours allude to the fundamental issue with colour determination through visual comparison with reference colours, as would be provided, for example, by the colour chips in the Munsell soil colour charts - different physical and psychophysical conditions dictate the eye-brain system's interpretation of the expressed colour (Melville & Atkinson 1985; Torrent & Barron 1993). This implies that any colour registered at any point of time is a consequence of the conditions under which the colour was determined, and that colour essentially remains a perception.

This conclusion allows one to predict that measured and perceived colour would never be exactly the same simply due to differences in the measurement conditions (Post et al. 1993). It is however encouraging to note that the results presented in Table 3.1 indicated that visual and spectroscopic colour determination of soils in a dry state both registered changes in the three applicable colour dimensions in a similar manner. The reported positive correlations imply that when the instrument recorded an increase in the *hue*, *value* and *chroma* of a soil, visual perception recognised a change in the same direction. The extent to which these perceived and measured colour variables can differ is nonetheless variable and reports thereof have been made by various authors. In the study done by Post et al. (1993) *value* was also found to be the colour variable most precisely and accurately determined by a panel of experienced soil scientists. These authors stipulated that *chroma* and *hue* were more difficult to evaluate compared to *value* due to the nature of the colour variation involved. The required colour sensitivity to accurately distinguish between particularly *chroma* is more complex than for *value* where a simple black to white scale is applicable. Although other studies have reported contrasting results where visual estimates of *value* tended to be higher and more irregular than the corresponding spectrophotometer readings (Barrett 2002; Viscarra Rossel et al. 2009), the colour discrimination thresholds of the human eye represented in Luo et al. (2001) provides some support to the explanation provided by Post et al. (1993). Luo et al. (2001) established that visual sensitivity to high *chroma* colours is low. This implies that the human eye has a limited ability to distinguish between highly saturated colours even if the colour differences are relatively great. In addition, although visual

colour discrimination thresholds are closer together at low *chromas*, they can still be influential. To complicate the matter even further, variability with regard to human ability to discern between colours of variable saturation appears to be *hue* related, with this phenomenon seemingly more intense towards the blue and green *hue* variables as opposed to red and yellow. This ability of *hue* to influence the recorded *chroma* and *vice versa* has been previously documented in a number of studies (e.g. Sánchez-Marañón et al. 2011).

From the presented results, *chroma* seems to be the most challenging colour dimension to visually interpret and accurately quantify. The complexity of *chroma* measurement is also substantiated by the statements of Barrett (2002) who concluded that visual *chromas* are apt to be more extreme than corresponding spectrophotometer measurements. During this investigation *hue* also presented some related challenges. The instrument's tendency to register lower *chromas* and redder *hues* is potentially a result of the enhanced sensitivity of the spectrophotometer in detecting changes in the reflectance characteristics of the soil brought about by different Fe oxide induced absorption bands in the different regions of the visible spectra (Bedidi et al. 1992). However, no certainty surrounding the extent of such influence on measured colours exist, and therefore in the light of the inconsistencies related to visual colour estimation (Melville & Atkinson 1985; Sánchez-Marañón et al. 2011), it would seem more appropriate to rather question why visual perception registered yellower *hues* and higher *chromas*. The proposed explanation is related to the perceptual colour space represented by the Munsell system and the consequent physical and psychophysical aspects that can influence the colour measurement outcomes in this model (Torrent et al. 1983). According to Barrett (2002), the extreme Munsell *chromas* reported in this author's study is partially attributed to a psychological preference on the part of the colour observer to report more extreme numbers to better differentiate among similar colours. The possibility that the higher perceived *chromas* presented in this study is the result of similar bias is a strong probability. In addition, the results by Sánchez-Marañón et al. (2011) indicated some ferrallitic soil samples tend to redden whilst others yellowed under changing daylight conditions in the field. In-field lighting conditions could therefore have been responsible for the more yellow soil colours that were perceived. These authors suggest the nature of the particular soil sample will control the intensity of the shift in its colour caused by similar changes in (day) lighting conditions.

Besides the psychological bias of the colour observer and the influence of lighting conditions, an additional psychophysical factor related to the book-format of the Munsell soil colour charts is also proposed to affect registered colour. Within the Munsell soil colour charts, every page represents a different *hue* with corresponding *value* and *chroma* scales. It is therefore proposed that perceived *hue* is essentially influenced by a 'book effect' where an observer rather tends to match a soil to a colour chip at a higher *chroma* than turn the page to compare it to a different *hue*. An observer is therefore



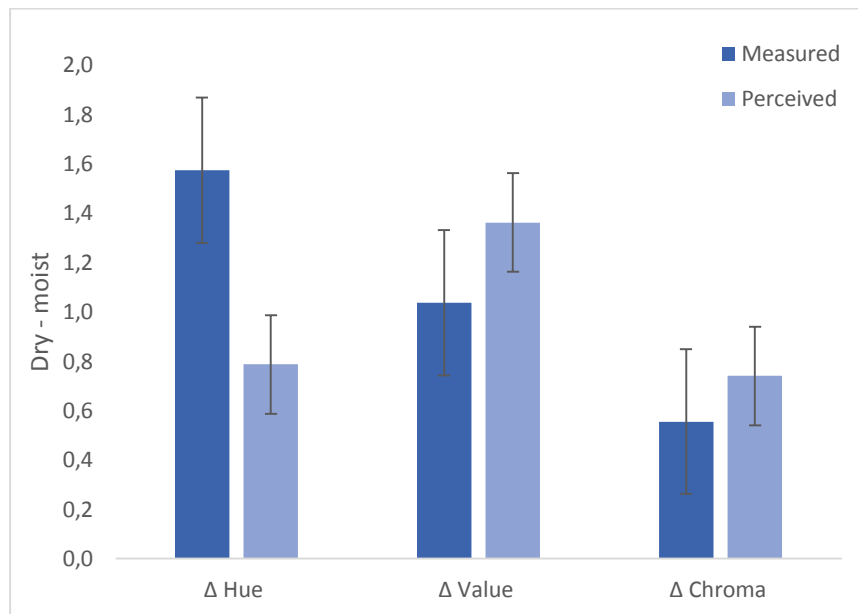
already tempted to assign a soil with a higher, richer *chroma* when a red or yellow soil is observed and only later consider changes to the soil *hue*. This phenomenon can aid in explaining both the higher perceived *hues* and *chromas* that were registered in this study.

It is important to recognise that differences between perceived and measured colours can significantly influence soil classification and characterisation outcomes. Unfortunately, the data generated in this study makes it impossible to state which of these measurement techniques are more accurate than the other. What can be concluded, however, is that various physiological factors have the potential to influence visual colour estimation and this, coupled with the statements made by amongst others Melville & Atkinson (1985) and Post et al. (1993) on the nature of spectroscopic colour measurement, provides enough evidence to state that spectrophotometer colour measurements in the laboratory will be less subjective and more precise compared to visual colour determination in the field. This is not to say that visual colour determination has no role to play in soil colour measurement, but rather that in-field soil colour determination should serve as a preliminary approach (Sánchez-Marañón et al. 2011). The accuracy and precision of this method will suffice for broad scale soil classification and mapping but more accurate applications will require the use of instruments and more controlled colour measurement conditions.

### 3.3.2 Colour measurement conditions: the addition of moisture

Upon the addition of moisture to the soil sample, variable outcomes under measured and perceived conditions for each of the colour variables were registered. In Table 3.1 the presented results indicate that perceived *hue* changed in a consistent manner in dry and moist soil samples ( $r=0.86$ ), whilst the same was true for measured *hue*, the only difference being a reported weaker positive correlation ( $r=0.51$ ) (Table 3.1). However, the perceived *value* of the soils in a dry and a moist state did not seem to co-vary ( $r=0.44$ ), whilst a weak negative correlation coefficient indicated that no consistent change in the measured *values* of dry and moist soil existed ( $r=-0.15$ ). In the case of *chroma*, perceived values under moist and dry conditions revealed correlated changes ( $r=0.70$ ) whilst measured *chromas* under these conditions proved to follow no consistent relationship ( $r=-0.09$ ) (Table 3.1). Again these correlation coefficients provided no information on the magnitude of change in each colour variable under the different measurement conditions from a dry to moist soil state. Therefore, the perceived and measured changes in *hue*, *value* and *chroma* from a dry to moist soil state was expressed as the mean difference between the determined dry and moist values. From Figure 3.2 it can be observed that both perceived and measured *hue* tended to decrease (i.e. redden) upon wetting although this decrease was significantly higher for instrument-measured *hues* compared to those visually determined ( $p=0.04$ ;  $F=4.28$ ). In contrast, the addition of moisture proved to effect perceived *value* significantly more than measured *value* with perceived *values* of moist soils being significantly lower

( $p=0.02$ ;  $F=5.26$ ) than those registered by the instrument. This implies that the average difference in *value* between wet and dry soil was greatest for visual measurements. Under both measurement conditions, however, *value* tended to decrease, implying a darkening of the soil as moisture was added. In the case of *chroma*, the addition of moisture also tended to result in lower values under both perceived and measured conditions but no significant difference was reported between the changes in *chroma* registered by the eye and instrument respectively from a dry to a moist soil state.



**Figure 3.2.** The average difference of measured and perceived hue, value and chroma from a dry to a moist soil state (dry-moist).

As previously stated, perceived *hue* and *chroma* were positively correlated between dry and moist soil states implying that the eye registered consistent changes in these variables between moist and dry soil conditions. Measured *hue* also exhibited a similar tendency but the changes in perceived *value* and measured *value* and *chroma* were not consistent between dry and moist soil. This eludes to the fact that the extent and direction of the colour change registered by the instrument upon the addition of moisture to the soil sample, differed from that which was visually perceived. Furthermore, the addition of moisture resulted in both a perceived and measured reddening of the soil, with the recorded *hues* being significantly lower in the moist state. This effect of moisture on *hue* was significantly more pronounced in measured compared to perceived colour. Results also indicated a decrease in the purity and saturation of the *hue* in the presence of soil moisture, as indicated by a decrease in *chroma*. This was the case irrespective of the measurement technique applied. Munsell *value* furthermore decreased under moist soil conditions resulting in a darker soil colour, with the reported darkening effect being significantly greater in visually perceived colours compared to spectrophotometer measurements. Based on the variation in soil colour in all three these visually

perceptual colour dimensions, it can be stated that for the soils under investigation, the addition of moisture resulted in significant colour variations.

According to Shields et al. (1966), the well-documented influence of moisture on soil colour relates to its substantial influence on soil reflectance properties. Bowers & Hanks (1965), Baumgardner et al. (1985), Post et al. (2000) and Barrett (2002) have all made reference to the darkening effect that moisture has on soil colour as a result of a decrease in the luminosity component, more specifically parameters such as Munsell *value* or CIELAB  $L^*$ . According to these authors this is the result of a decrease in surface reflectance brought about by a thin liquid film that covers the soil mineral particles. Bedidi et al. (1992) studied colour variations in the presence of soil moisture in lateritic soils with very similar colour characteristics as those under investigation in this study and also found this decrease in *value* with the addition of moisture. More importantly however, these authors together with Post et al. (1993) recorded a shift in *hue* towards red colours at high moisture levels and also a systematic decrease in the *chroma* under such conditions. According to Bedidi et al. (1992) the changes in the soil spectral properties with the addition of moisture depends upon the soil's mineral composition, where lateritic soils rich in Fe oxy-hydroxides exhibit more complex spectral behaviour in the presence of moisture due to this medium's influence on the variable absorption bands produced by these minerals between 400 nm and 700 nm, that define the soils spectral reflectance characteristics.

The explanation provided in the study by Bedidi et al. (1992) states that the total reflectance of a particulate medium can be dominated by either a specular (photons reflected at the surface of the medium) or volumetric (sum of all the reflected radiation passed through the particles) component. The dominance of either one of these components is the result of the optical and geometrical properties of the grains as well as optical properties of the medium surrounding the particles. Hematite and goethite covering soil grains have variable absorption intensities in the red, green and blue regions of the visible spectra. This is furthermore modified by refractive properties of the surrounding medium i.e. the addition of water will cause a change in the scattering properties of soil particles and the balance between absorption and scattering in the soil medium. In these Fe oxide dominated soils, the red region bands were found to be dominated by the volumetric component resulting in a decrease in total reflectance when moisture is added due to the low reflectance properties of water. The dominant wavelength however, increases in such soils under these conditions resulting in a redder appearance. Different combinations of these oxide minerals can furthermore influence the purity of the *hue* and this can explain the decrease in *chroma* values. In conclusion, the reflectance variations in Fe oxide dominated soils are in its own sense complex, with the addition of moisture further complicating spectral reflectance in these soils. Bedidi et al. (1992) state that any

material containing the same absorbent species in the different visible spectral regions should induce similar changes in reflectance when moistened.

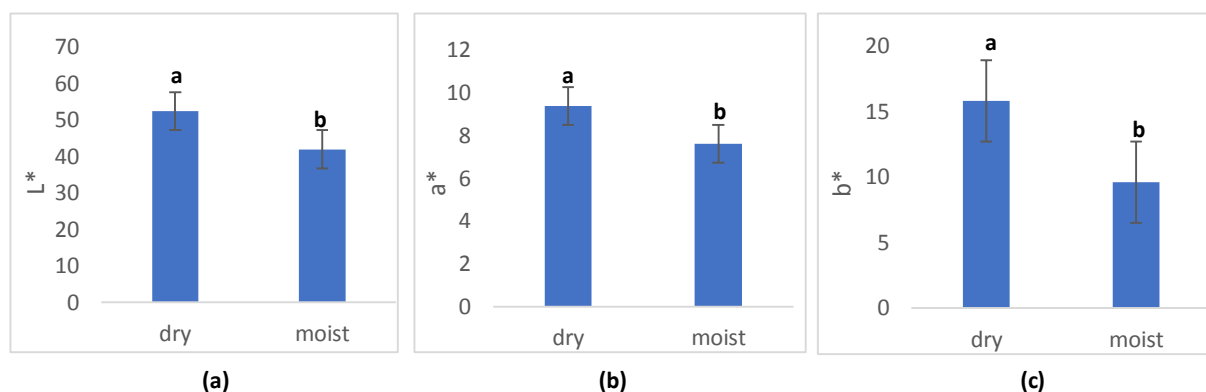
The greater sensitivity of the instrument in detecting changes in the reflectance properties of the soil sample as well as its ability to more precisely quantify the interaction of the soil medium with the added moisture was most probably the reason why the difference in Munsell *hue* between dry and moist samples was greater when determined with the spectrophotometer compared to visual means. The human eye would simply be unable to record what the influence of moisture would be in such detail. Similarly, based on the above discussed influence of moisture on soil reflectance properties as well as the sensitivity of the instrument to changes in spectral reflectance characteristics, it is not surprising that moist measured *values* (or any other colour variable in the moist state) are not similar to those determined through visual perception. According to Torrent & Barron (1993), the consistent preparation of moist samples poses a challenge, with the importance of the quantity of water added to the sample being that it can result in different spectral changes (Bedidi et al. 1992). One would expect moisture quantity to have less of a significant influence on the coarse-scaled visual estimation but that instrumental measurements might record a more exact change. This is proposed to be a potential reason why unpredictable changes in the measured *value* and *chroma* of moist soils were recorded.

What was interesting is the fact that Munsell *value* was visually perceived to decrease more drastically under moist conditions compared to what the instrument registered. This can be attributed to psychophysical bias on the part of the colour observer where the addition of moisture is known to result in a darkening of the soil and as a result the observer might unconsciously over-exaggerate the darkening effect. The previously discussed 'book effect' could similarly also be applicable to Munsell *value* in this regard. Essentially the colour observer tends compensate for colour variation in *chroma* or *value* rather than in *hue*. So unconsciously the observer registers a lower *chroma* or *value* whilst a change in *hue* might be required. Additional evidence in support of this theory can be seen in Figure 3.2, where the effect of moisture is significantly greater in measured compared to perceived *hues* whilst perceived *value* is significantly greater than measured *value*. This suggests that the instrument accounts for some of the wetting-induced colour change in the *hue* dimension while, visually *value* is predominantly used to account for the colour change brought about by the addition of moisture.

Despite the dissimilarities in the way moisture-induced colour changes are registered using these two techniques, moist soil samples seem to be perceptually more chromatic. The implications thereof for soil classification is significant. A prime example, is of course, the distinction between grey and yellow diagnostic E horizons in the South African soil classification system (Soil classification working group

1991). It is prescribed that yellow E horizons be identified in the moist state, with the rationale being that under these circumstances the pigmenting effect of the limited Fe oxides that are present in such soil horizons are enhanced. This is of course also pertinent to the bleaching phenomenon, where in many instances, bleached topsoils are overlooked due to the fact that a profile is moist. The results from this study indicate that moisture can induce some chromatic changes in the soils and that when dealing specifically with pale-coloured horizons, colour must be measured under both dry and moist conditions before any conclusions about soil condition can be reached.

In addition to the Munsell colour space model, the spectrophotometer also measures colour in CIELAB tristimulus values thereby providing an additional colour space model within which the effect of moisture on soil colour could be investigated. From Figure 3.3a it can be observed that  $L^*$  is significantly higher for soil samples in the dry state compared to when moisture was added ( $p \leq 0.01$ ;  $F=902.99$ ). The same was also observed for  $a^*$  ( $p \leq 0.01$ ;  $F=239.43$ ) (Figure 3.3b) and  $b^*$  ( $p \leq 0.01$ ;  $F=1018.7$ ) (Figure 3.3c). Figure 3.3a furthermore shows that with the addition of moisture,  $L^*$  decreased with an average of 10.4 units. Of all the CIELAB values,  $L^*$  is the only component that has defined values ranging from 0 (black) to 100 (white) (CIE 1986) which enables us to conclude that the addition of moisture resulted in significant darkening of the soil sample.



**Figure 3.3.** The difference in the instrument-measured CIE  $L^*$  (a),  $a^*$  (b) and  $b^*$  (c) values between dry and moist soil samples. Significance letters and standard error bars are indicated.

Due to the lack of predefined value ranges for both  $a^*$  and  $b^*$  (CIE 1986; Hill et al. 1997), interpreting these values in a similar manner as  $L^*$  would be inappropriate. According to Mahy et al. (1994), tristimulus colours can only be used to see if colours match but they cannot predict the visual difference if no match is obtained. If one is to determine whether a statistically defined difference in these colour variables would be of any practical significance i.e. visually detectable, these authors state that uniform colour spaces should be developed and individual colours should be represented within such spaces for comparison sake. Hill et al. (1997) similarly stated that to be able to represent and compare colours in a CIE  $L^*a^*b^*$  colour space, axes ranges and limitations need to be specified. These authors developed an optimal CIELAB colour space arrayed within the limits  $0 \leq L^* \leq 100$ ,  $-166$

$\leq a^* \leq 141$  and  $-132 \leq b^* \leq 147$ . Although these values provide little insight into scales of significant difference for these colour variables, they do provide some reference. However, Mahy et al. (1994) state that “there are quite a lot of uniform colour spaces that are optimized to predict certain experimental data, but there is no guarantee that such a space is also able to approximate other experimental data”. It would therefore seem more appropriate to interpret  $a^*$  and  $b^*$  colour components for a particular study based on the variation in values generated for each of these components within the confines of the individual study. From the provided results it is evident that statistically significant differences for both  $a^*$  and  $b^*$  values occur between the dry and moist soil states. The mean unit differences are 1.7 and 6.2 respectively. If these mean differences are compared to combined standard deviations of moist and dry  $a^*$  and  $b^*$  values respectively ( $a^*=2.30$ ;  $b^*=4.26$ ), it seems that the statistical significant difference recorded for  $a^*$  is of less relevance than that for  $b^*$ . It is however not possible to definitively state that visible colour differences along these colour components would be observed with these measured changes. Therefore, it is concluded that in theoretical terms these changes in  $a^*$  and  $b^*$ , brought about by the addition of moisture, would relate to a tendency towards greener colours along the  $a^*$  axis (Figure 3.3b) and more blue colours along the  $b^*$  axis (Figure 3.3c). Based on the nature of the colours dealt with in this study, it would be more appropriate to rather interpret these changes brought about by the addition of moisture to the soil as a decrease in the red colouration along the  $a^*$  axis and a decrease in the yellow colouration along the  $b^*$  axis.

The reported decrease of the  $L^*$  value and the theoretical darkening of the soil that it implies is in agreement to what was reported for Munsell *value*. The presented decrease in both  $a^*$  and  $b^*$  in the presence of soil moisture and therefore the theoretical decrease in the red colouration along the  $a^*$  axis and a decrease in the yellow colouration along the  $b^*$  axis, however, seems to be in contradiction to the colour change registered in the Munsell colour space. Upon the addition of moisture Munsell *hue* tended to decrease, signifying a reddening effect. To explain this apparent discrepancy it is important to note that this reddening phenomenon in the Munsell colour space refers to an increase in redder *hues* but at the expense of yellower *hues*. This is the consequence of linear hue scale applied in this study. In the CIELAB colour space the recorded decrease in red colour is accompanied by a simultaneous decrease in yellow. Therefore, these results clearly indicate that changes in the CIELAB colour space should not be regarded as perceptual colour changes as would be the case within the Munsell system and direct comparisons between the colour variations in these two colour space models are complex. Data from this study suggests that a relationship between  $a^*$ ,  $b^*$ , *hue* and *chroma* exists. This implies that changes in  $a^*$  or  $b^*$  in the CIELAB colour system is shared between Munsell *hue* and *chroma* and *vice versa*. It is unfortunately not possible to state what numerical changes in

which CIELAB colour dimension is responsible for visible changes in the soil. The different dimensions of colour that are signified by each colour variable in the different colour space models will definitely overlap but can still be profoundly different, making direct comparisons quite impossible. Furthermore, the value ranges and scales of the individual colour variables in each colour space model will also differ complicating these comparisons even more. It must therefore simply be concluded that for future comparison to soil colours measured using the CIELAB colour space model, the addition of moisture resulted in lower  $L^*$ ,  $a^*$  and  $b^*$  values.

### 3.3.3 *Soil property-colour relationships*

The aim of this section is to determine which soil properties affect soil colour expression in which dimension of colour change. Although most of the work done on colour throughout this study was completed using the Munsell HVC colour space, an important comprehension regarding the nature of colour quantification using these colour dimensions needs to be made. The methods applied for measuring soil colour in this study entailed measuring each Munsell soil colour chip in the CIELAB colour space and using the generated  $L^*$ ,  $a^*$  and  $b^*$  value ranges for these chips to specify Munsell target colours. The colour of a soil would therefore be measured in  $L^*$ ,  $a^*$  and  $b^*$  values and automatically be transposed to a Munsell colour based on the correlation between the LAB values measured for the soil and that which has been specified for the target Munsell chips. This was necessary to be able to distinguish bleached soils from non-bleached variants in a precise and objective manner. However, this process resulted in the loss of information simply because the unit scales used in the CIELAB colour space are continuous whereas in the Munsell colour space these continuous LAB values were categorized into the coarser and more discrete Munsell HVC units. The problem is that when trying to detect which soil properties are responsible for soil colour, these discrete Munsell units are less sensitive to change because they are based on perceptual differences and not changes in spectral reflectance. Keeping this in mind, correlations and comparisons between soil properties and perceived and measured Munsell and CIELAB variables were nonetheless made.

Separate Spearman-r correlation matrices were generated to investigate the relationships between i) the different colour variables (Appendix 3.2), and ii) the different physical and chemical soil parameters (Appendices 3.3). An inspection of these relationships were deemed necessary before any investigation into the relations between soil properties and expressed colour could be launched. The combined correlation matrix demonstrating the relationships between all the determined soil parameters and the corresponding soil colour variables are featured in Appendix 3.1. An extract of this matrix including some selected soil parameters and soil colour variables are included in Table 3.2 and will be discussed in more detail. A Multiple Factor Analysis (MFA) was also conducted and the resulting MFA correlation circle is attached in Appendix 3.4.

From the generated correlation coefficients, positive correlations between measured and perceived Munsell *value* and instrument-measured  $L^*$  were observed ( $r=0.86$  &  $r=0.56$ , respectively) (Appendix 3.2). This was anticipated seeing that both Munsell *value* and  $L^*$  are measures of the lightness of a colour in the Munsell HVC and the CIELAB colour systems respectively (Viscarra Rossel et al. 2006). In addition, measured and perceived Munsell *chroma* was found to be correlated with instrument-measured  $a^*$  ( $r=0.65$  &  $r=0.78$ ) whilst only measured *chroma* was related to  $b^*$  ( $r=0.74$ ) (Appendix 3.2). Similar to *chroma*, measured and perceived Munsell *hue* was also significantly related to  $a^*$  ( $r=-0.50$  &  $r=-0.67$ , respectively) but did not show any relation to  $b^*$  ( $r=0.00$  &  $r=-0.01$ ) (Appendix 3.2). Per definition, *chroma* is a measure of the pureness of a colour or the saturation of the hue (Munsell Color Company 1980) whilst  $a^*$  and  $b^*$  respectively represent a red-to-green and blue-to-yellow scale (Melville & Atkinson 1985; Viscarra Rossel et al. 2006). A higher *chroma* would therefore imply a more wholesome colour whereas a change in  $a^*$  or  $b^*$  would signify a colour theoretically becoming more red/green or yellow/blue. The agreement between these colour variables is therefore also expected.

With regards to the determined soil parameters, no unexpected relationships between any of the physical or chemical soil characteristics were detected (Appendix 3.3). Positive correlations between the different extractable Fe and Al phases (Spearman-r:  $Fe_{CBD}$  vs  $Fe_{AAO} = 0.66$ ;  $Al_{CBD}$  vs  $Al_{AAO} = 0.70$ ;  $Fe_{CBD}$  vs  $Al_{CBD} = 0.78$ ;  $Fe_{AAO}$  vs  $Al_{AAO} = 0.65$ ) as well as between the individual particle size fractions existed. Based on these correlations,  $Fe_{CBD}$  was deemed to be a good representation of the total Fe content of the soil (Loeppert & Inskeep 1996).



**Table 3.2.** Spearman-r correlation coefficients indicating the relationships between some selected soil parameters and the determined soil colour variables. Correlations were deemed to be significant > 0.5 (bold). (Complete correlation matrix included in Appendix 3.1)

	Fe <sub>CBD</sub> (%)	Fe <sub>AAO</sub> (%)	Al <sub>CBD</sub> (%)	Al <sub>AAO</sub> (%)	Fe CI <sup>1</sup>	C (%)	C:N	ESP	Ca:Mg	Total Sand (%)	Total Silt (%)	Co Silt (%)	Fi Silt (%)	Total Clay (%)	Co Clay (%)	Fi Clay (%)	WDC (%)
Perceived Hue	<b>-0.56</b>	-0.31	-0.23	-0.31	0.38	0.16	0.19	-0.03	0.08	0.27	-0.17	0.03	-0.22	-0.47	-0.43	-0.42	0.00
Measured Hue	-0.26	-0.14	-0.05	-0.10	0.13	0.14	0.15	-0.06	-0.13	0.02	-0.01	0.20	0.06	-0.24	-0.22	-0.28	0.04
Perceived Value	-0.20	-0.07	-0.02	-0.11	0.21	-0.12	0.16	0.18	-0.01	-0.08	0.10	0.17	0.08	-0.08	-0.05	-0.24	0.11
Measured Value	-0.04	0.16	0.16	-0.04	0.20	0.13	0.06	0.43	-0.17	-0.40	0.47	0.32	0.47	0.08	0.16	-0.39	0.45
Perceived Chroma	<b>0.54</b>	0.34	0.49	0.50	-0.38	-0.34	-0.02	-0.01	0.02	-0.25	0.20	0.18	0.15	0.50	0.44	<b>0.63</b>	-0.14
Measured Chroma	0.47	<b>0.57</b>	<b>0.57</b>	0.40	-0.09	-0.07	-0.13	0.36	-0.43	<b>-0.61</b>	<b>0.58</b>	0.31	<b>0.54</b>	<b>0.58</b>	<b>0.62</b>	0.22	0.34
L*	0.12	0.30	0.35	0.12	0.15	0.12	0.06	<b>0.62</b>	-0.36	<b>-0.59</b>	<b>0.64</b>	0.36	<b>0.62</b>	0.33	0.41	-0.22	<b>0.54</b>
a*	<b>0.75</b>	<b>0.58</b>	<b>0.59</b>	<b>0.59</b>	-0.38	-0.28	-0.17	0.20	-0.26	<b>-0.58</b>	0.50	0.33	0.46	<b>0.73</b>	<b>0.71</b>	<b>0.56</b>	0.10
b*	0.42	<b>0.53</b>	<b>0.63</b>	0.44	-0.05	-0.10	0.00	<b>0.52</b>	-0.41	<b>-0.68</b>	<b>0.66</b>	0.42	<b>0.62</b>	<b>0.59</b>	<b>0.63</b>	0.15	0.33

<sup>1</sup> Fe CI (crystallinity index) = Fe<sub>AAO</sub>/Fe<sub>CBD</sub>

Based on the premise that the expression of colour in a soil is a result of the interaction between different physical soil properties and the present chemical constituents, it was proposed that specific soil physical and/or chemical characteristics will be responsible for colour variation in a specific colour dimension, with the most influential properties essentially exhibiting the greatest correlation to a specific colour variable (Viscarra Rossel et al. 2006). Upon relating soil features to colour expression it was concluded that the majority of the determined soil parameters had no significant influence on soil colour (see Appendix 3.1). The soil's Fe content, however, proved to be predominantly responsible for the variation in Munsell *hue* and *chroma* in the sampled soils, with *hue* and *chroma* respectively being negatively and positively correlated to Fe<sub>CBD</sub> content (Table 3.2). Interestingly, in the case of *hue*, this relationship was only significant in perceived *hues* ( $r=-0.56$ ) and not in instrument-measured *hues* ( $r=-0.26$ ). What is noticeable is that the relationship between *hue* and Fe<sub>CBD</sub> is negative under both measurement conditions which is the result of the manner in which Munsell *hue* was arranged during statistical analysis. The negative relationship essentially entails that as the soil's Fe content increased, a reddening of the soil occurred.

The recorded positive correlation between *chroma* and Fe<sub>CBD</sub> is in agreement with the results obtained by Soileau & McCracken (1967) and applied to both measured and perceived *chromas* although measured *chromas* exhibited a slightly poorer relationship to Fe<sub>CBD</sub> content ( $r=0.54$  &  $r=0.47$ , respectively) (Table 3.2). This positive correlation implies that with an increase in Fe, *hue* becomes more saturated and the soil colour more pure. In simple terms, more Fe resulted in a more pronounced and chromatic soil colour.

These recorded results strengthen the opinion that Fe is one of the main pigmentation agents in the soil environment (Torrent et al. 1983; Barron & Torrent 1986; Sánchez-Marañón et al. 2004) and more importantly within the diagnostic soil horizons investigated within this study (Soil classification working group 1991; Fey 2010). One must however keep in mind that the soils under investigation ranged in colour from grey to yellow to red and that the recorded reddening of a soil according to the Munsell *hue* scale applied in this investigation represents a similar change from yellow to red. This reddening phenomenon as well as the increase in the strength of the colour that accompanied an increase in Fe content is a result of the nature of Fe oxide-related soil colour expression. The two most abundant secondary Fe oxides present within soils are goethite and hematite (Torrent et al. 1983; Schwertmann & Taylor 1989). The presence of goethite is usually indicated by yellower soil colours, whilst hematite is responsible for a more reddish appearance (Davey et al. 1975; Bigham et al. 1978; Torrent et al. 1983). The presence of either will essentially determine the *hue* of the soil sample in the absence of other soil pigmenting agents. The reddening phenomenon observed with an increase in Fe content can therefore be the result of an increase in the hematite content of the soil (Torrent & Barron

1993). In addition, an increase in the quantity of either goethite or hematite would also have an enhanced pigmenting effect and result in more pure red or yellow soil colours, although Barron & Torrent (1986) have reported that threshold saturation percentages (about 10% for hematite and 30% for goethite) above which higher Fe contents do not affect colour change do exist. The weak correlation that was observed between  $Fe_{CBD}$  and  $b^*$  ( $r=0.42$ ; Table 3.2) further implies that red Fe oxides and therefore hematite was most probably the dominant pigmentation agent in the sampled soils and that redder soil colours were more dominant than yellow variations. This also agrees to some extent with the reported redder *hues* that were registered by the instrument in the overall soil dataset. It is not however suggested that goethite was not present in significant quantities. Various studies have proven hematite to be a much stronger pigmenting agent than goethite, with red colours often masking the yellow colours of goethite or only small quantities of hematite being required to give soil a predominantly reddish appearance (Childs et al. 1979; Torrent et al. 1983; Barron & Torrent 1986).

The expression of Fe oxide-induced colours, however, proved to be quite complex as discrepancies were reported between perceived and measured colour variables and the corresponding soil  $Fe_{CBD}$  content. Visual colour determination registered a reddening in soil colour with an increase in the soil Fe content as indicated by the presented negative relationship between perceived *hue* and  $Fe_{CBD}$  ( $r=-0.56$ ; Table 3.2). The absence of such a relationship between instrument-measured *hues* and  $Fe_{CBD}$  ( $r=-0.26$ ) was therefore somewhat confusing and initially interpreted to imply that the instrument was less sensitive to the pigmenting effect of increased levels of Fe oxides (e.g. hematite). However, the fact that a strong positive relationship ( $r = 0.75$ ) exists between  $Fe_{CBD}$  and  $a^*$  suggests that the instrument is sensitive to the reddening effect of increased Fe and that these discrepancies between perceived and measured *hue* and the soil  $Fe_{CBD}$  content is most likely a result of the colour data processing, as explained in the first paragraph of this discussion. Such complexities in relating soil spectral properties to Munsell notation have been recorded in the past (Escadafal et al. 1989).

Within this study, the method used to translate LAB colours to Munsell notation resulted in a loss of information. The steps in this method entailed measuring colour in continuous LAB values which was then transposed to discrete Munsell HVC units that have been established to represent perceptual colour differences. Consequently, measuring colour in LAB units and transposing it to Munsell HVC is an oversimplification of the colour spectrum which, when correlating the transposed HVC values to soil properties will result in weak correlations between instrument-measured Munsell values and corresponding soil properties. In the case of Munsell *hue*, the entire red-yellow spectrum was essentially forced into only 4 *hue* targets (2.5YR; 5YR; 7.5YR and 10YR) and such a compartmentalisation of LAB values, whilst necessary for categorising soils into bleached and non-

bleached groups, does not translate well for linear correlations with soil parameters. Nonetheless, even if measured Munsell *hue* presented no reddening effect with increasing Fe content, the reddening of the soil that was visually observed coupled with the reddening changes along the  $a^*$  dimension of the CIELAB colour space implies that Fe had a reddening effect on soil colour and that in most instances the redder soils that were sampled as part of this study had the greatest  $Fe_{CBD}$  contents. Essentially, if Fe content is taken into consideration, visual perception exaggerated the pigmenting effect of the Fe oxides to suit the Munsell HVC scales whilst the instrument registered more gradual colour changes. Therefore, although soils reddened in the presence of increased Fe (hematite) as suggested in  $a^*$ , the instrument did not register these changes on a scale where it would induce *hue* changes in the Munsell colour space model as was visually perceived.

In addition, it must also be kept in mind that a redder *hue* within the context of this study implies a *hue* closer to the red end from an arbitrary position in the yellow *hue* spectrum along the general *hue* scale. Therefore, the change from a predominantly yellow soil (10YR) to a slightly lesser yellow soil (7.5YR) forms part of the reddening phenomenon described in this study. The fact is that such colour changes are not necessarily solely related to increases in hematite but can rather also just be the result of lower concentrations of goethite on the surfaces of the mineral surface particles or variability in the crystallinity of the goethite that was present. The sensitivity of the instrument in detecting such subtle changes can furthermore contribute to the lack of a relationship between measured *hue* and  $Fe_{CBD}$  simply because the *hue* scale applied in this study views red and yellow soil colour to be interchangeable, whilst in reality this is not the case. Noticeably, poorly crystalline Fe phases were not perceived to have specific colour influence, as illustrated by the absence of a relationship between perceived *hue* or *chroma* and poorly crystalline  $Fe_{AAO}$  (Table 3.2). No significant relationship was recorded between any of the visually determined colour variables and the degree of Fe crystallinity represented by the Fe CI (Table 3.2). The instrument however exhibited an enhanced sensitivity towards the influence of poorly crystalline Fe on Munsell *chroma*,  $a^*$  and  $b^*$  eluding to an ability of the instrument to detect spectral reflectance changes brought about by more amorphous, and presumably also more irregular surfaced, Fe oxides. The widely accepted notion is however that hematite and goethite are the Fe oxides predominantly responsible for red and yellow soil colours and that these oxides represent more crystalline Fe phases (Schwertmann & Murad 1983; Cornell et al. 1987).

From the above presented data it is clear that Munsell *hue* posed the greatest challenge in relating colour change to soil properties in this study. This is primarily due to the coarser nature of the *hue* scale compared to that of *value* and *chroma*. Both Munsell *value* and *chroma* follow more continuous

numerical scales which not only make linear correlations to soil parameters more suitable, but will most probably also be slightly more suited for transposing colours from LAB units to Munsell HVC using the method applied in this study. As an example, it was expected that a relationship between *hue* and *chroma* would exist based on their reported correlation to Fe-induced colour expression in the soil. It was found that only perceived *hue* and *chroma* presented a noteworthy negative correlation ( $r=-0.52$ ), whilst no relationship existed between measured *hue* and *chroma* ( $r=-0.20$ ) (Appendix 3.2). As previously reported, both *hue* and *chroma* did however correlate well to  $a^*$  (Appendix 3.2). In the case of perceived *hue*, a negative correlation to  $a^*$  was reported whilst measured *hue* exhibited a much weaker negative relationship. Both measured and perceived *chroma* on the other hand displayed strong positive correlations to  $a^*$ . These results substantiate the statements regarding the colour measurement methods and the consequent loss of information by indicating that this effect was less pronounced for the Munsell variables that follow a more 'continuous' numerical scale such as *chroma* as opposed to Munsell *hue*.

Munsell *value* and  $L^*$  did not seem to be correlated to any of the known soil pigmenting agents in this study. This lack of a relationship between soil luminosity (*value*,  $L^*$ ) and the determined soil parameters can be explained by looking at the soil features most pertinently responsible for darker or lighter soil colouration. In the literature both organic material and soil moisture content are deemed to be responsible for a darkening effect and therefore a decrease in Munsell *value* and  $L^*$  (Baumgardner et al. 1985; Post et al. 1993; Schulze et al. 1993; Rabenhorst & Parikh 2000; Sánchez-Marañón et al. 2004). Although the organic C content of the sampled horizons were determined, organic matter was present in such low quantities in the soils under investigation, that it proved to have no significant influence on soil colour expression. In addition, the soil colour variables used for comparison with soil physical and chemical properties were all measured in the dry state. This was to avoid any inconsistencies associated with the soil moisture content at which colour is determined. In conclusion, no relationship between *value* and any of the included soil parameters were detected simply because the soil parameters that are known to be the most influential to colour change in this dimension either proved to be insignificant or was not investigated during this part of the study. What was interesting to note was the recorded relationships between the instrument measured  $L^*$  values and the different particle size fractions, as well as the soil's ESP (Table 3.2).

In support of the results presented, Torrent et al. (1983) and Rabenhorst & Parikh (2000) state that Fe oxides are the most important pigmenting agent in soils that have a low organic matter content. Besides Fe oxides and organic matter, the soil's state of aggregation and moisture content is the only additionally reported features known to effect the expressed soil colour (Sánchez-Marañón et al.

2004). The particle size distribution of the soil in some studies have also proved to influence the spectral reflectance characteristics of the soil medium thereby also theoretically altering soil colour (Bowers & Hanks 1965; Baumgardner et al. 1985; Sánchez-Marañón et al. 2004). Within this study, the different particle size distributions exhibited a definite relation to the recorded soil colours (Table 3.2). Whether the separate sand, silt and clay fractions play an active role in the colouring of the soil seems highly unlikely, but there is a strong correlation between the distribution of these size fractions and specifically instrument-determined Munsell *chroma* and the  $L^*$ ,  $a^*$  and  $b^*$  values. Measured *chroma* and  $b^*$  was negatively correlated to the soil's sand fraction ( $r=-0.68$  &  $r=-0.61$ , respectively) and accordingly displayed a positive relationship with both the silt ( $r=0.58$  &  $r=0.66$ ) and clay ( $r=0.58$  &  $r=0.59$ ) fractions (Table 3.2). In contrast, perceived *chroma* was only related to the fine clay fraction ( $<0.0002$  mm) ( $r=0.63$ ). The measured  $L^*$  values were negatively related to the sand fraction ( $r=-0.59$ ), positively related to the silt fraction ( $r=0.64$ ) and showed no relation to the clay fraction ( $r=0.33$ ). The  $a^*$  values were also negatively related to the sand fraction ( $r=-0.58$ ) of the soils and accordingly displayed a strong positive correlation to the different clay fractions that were present ( $r=0.73$ ). For all these colour variables the negative relationship that exists with the sand fraction implies that any increase in either of the Munsell dimensions or the CIELAB values are in actual fact related to increases in the silt and/or clay fraction of the soil. Therefore, the expressed colour variations recorded in the different colour dimensions are related to changes in the finer soil fractions. As can be expected, these finer soil fractions also show relatively strong positive correlations to the extractable Fe and Al phases (Appendix 3.3). This series of correlations are proposed to be the result of the larger surface area of the finer soil fractions and consequently the ability of the soil particles to adsorb more pigmenting Fe oxides. This would explain the positive correlation between *chroma*,  $a^*$  and  $b^*$  and the silt and clay fractions of the soil. What is interesting to note is the increase in  $L^*$  as the silt fraction of the soil increases. Greater  $L^*$  values alludes to lighter soil colours and potentially also the loss of pigmentation agents. Importantly, the influence of particle size could almost exclusively be observed with measured soil colour variables therefore one must not neglect to account for the variation in the spectral reflective properties of the individual soil particles and their influence on what soil colours are registered (Bowers & Hanks 1965; Baumgardner et al. 1985; Sánchez-Marañón et al. 2004). In most of the research that has been done, a decrease in the particle size of a soil sample results in an increase in spectral reflectance which constitutes an overall lighter colour. These changes, as supported by the lack of a relationship between the particle size fractions and the determined Munsell *values*, are mostly not visually detectable.

The fact that a wide range of particle size distributions were recorded in the sampled soils and that colours ranged from red to yellow to grey/bleached complicates clear conclusions about the

relationship between the expressed soil colours and the accompanying particle size distributions of the soils. Again, the different size fractions play no role as active pigmentation agents in the soil but the fact that especially the finer soil fractions have higher surface areas imply that these fractions can affect soil colour.

### 3.4 CONCLUSIONS

The comparison between visual colour assessment and spectroscopic colour measurement in the Munsell colour space revealed certain discrepancies. Although the presented data indicated that the direction of colour changes in each of the Munsell colour dimensions were similarly registered between these two measurement techniques, the generated colour variables did not always correspond under all circumstances. In the case of Munsell *hue*, visual and spectroscopic colours predominantly agreed although the instrument tended to register slightly redder *hues* (by approximately one hue unit). The reported Munsell *values* showed only slight differences between perceived and measured colours and it was concluded that *value* is the Munsell colour dimension that can be most precisely determined through visual means. The highest variability was recorded between perceived and measured *chroma*. The instrument tended to consistently register lower *chromas* (up to three chroma units), indicating that the eye perceived the soils to be brighter and more chromatic and, as a result, was less sensitive towards detecting bleached horizon colours. Due to the nature of the colour variation involved with the *chroma* dimension of the Munsell colour space it was concluded that this colour variable is the most difficult to determine through visual comparison to soil colour chips.

The soil colour variations brought about by the addition of moisture were also not similarly registered between the spectrophotometer and visual perception. It was determined that although soil colour changes significantly from a dry to a moist state, the instrument record this effect across both Munsell *hue* and *value* whereas visual colour determination tend to predominantly register the changes in Munsell *value*. The enhanced sensitivity of the instrument towards changes in the soil's reflective properties, the addition of unstandardised quantities of moisture to the soil samples, as well as a range of physical and psychophysical features influencing the way soil colour is perceived, are proposed to explain these differences within the dataset. Nonetheless, both the instrument and visual perception reported a darkening effect with the addition of moisture to the soil sample, as indicated by the decrease in both  $L^*$  and *value*. Furthermore, the addition of moisture also resulted in lower  $a^*$  and  $b^*$  values within the CIELAB colour space, but a lack of predefined value ranges for these variables disallow any assumptions about the perceivable colour differences represented by these changes.



Due to the reported precision of spectrophotometer colour measurements, a series of physical and psychophysical conditions were put forward to explain why visual perception and spectrophotometer readings did not always agree. The outcome was that soil colour remains a perception that is dictated by the measurement conditions under which it is determined. These conditions are more variable during visual compared to spectroscopic colour interpretations. As a result, visual colour determination will suffice in broad-scale soil classification ventures but for more accurate applications of soil colour, instrument measurements is a prerequisite.

With regards to the relationship between soil colour expression and soil chemical and physical properties, it was concluded that Fe oxides are the main pigmentation agents in the soils that were sampled for this study. The predominantly red and yellow-brown colours caused by respectively hematite and goethite were reported in both top- and subsoil horizons, excluding of course the bleached topsoil variants that also formed part of this study. An increase in the soil Fe content resulted in a perceived reddening in the Munsell soil colour space as indicated by the reported redder *hues*. Similarly, this reddening phenomenon was also observed in the CIELAB colour space, where more Fe resulted in greater  $a^*$  values. What was interesting to note was that the reddening effect of Fe was not observed in the spectrophotometer measured Munsell colours, which was attributed to the colour data processing techniques that were applied in the study. This observation in addition also alluded to the coarser and more discrete unit scale of the Munsell colour space which cautions its use in studies aimed at generating linear correlations between colour and soil properties.

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**CHAPTER 4: THE PEDOGENETIC ORIGIN OF BLEACHED TOPSOIL HORIZONS IN WEAKLY STRUCTURED SOIL PROFILES OF THE WESTERN CAPE AND MPUMALANGA PROVINCES OF SOUTH AFRICA**

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**4.1 INTRODUCTION**

The pedogenetic processes that are proposed to be responsible for the removal of soil pigmentation agents and the consequent expression of bleached colours within a soil horizon includes Fe reduction and loss (Fritsch & Fitzpatrick 1994; Cox et al. 1996; Peterschmitt et al. 1996; He et al. 2003), podzolization (Davey et al. 1975; Soil classification working group 1991; Zaidel'man 2007) and clay eluviation (Zaidel'man 2007; Fey 2010; Van der Waals 2013). Due to the specific environmental, climatic and geological conditions required for the development of podzolic soils (Lundström 2000) and the limited distribution of such conditions across South Africa (Fey 2010), bleaching as a result of podzolization is deemed to be a regional phenomenon. The processes of Fe reduction and clay eluviation, however, are more widespread and common features in many South African soils.

The reductive loss of Fe from a soil horizon is well understood. This microbial-mediated process results in the reduction of ferric Fe in oxide minerals and the consequent formation of ferrous Fe, a more solubilised Fe phase that is easily transported through soil solution (Wheeler et al. 1999; Rabenhorst & Parikh 2000; Thompson et al. 2006). The redox potential at which such a transformation will take place is strongly dependent on the soil pH, although various other factors are also influential. Seasonal fluctuations in soil water content as a result of variations in rainfall and evapotranspiration generates alternating conditions of Fe reduction and oxidation within the soil (Thompson et al. 2006). Van Huyssteen et al. (2010) proposed that a saturation of 70% pore space is sufficient to bring about reduction in the soil environment. During wetter periods reduction will result in the mobilization of Fe and its movement through the soil profile. Upon the subsequent drying-out of the soil matrix, ferrous Fe is again oxidized to ferric Fe in the presence of oxygen resulting in the deposition and accumulation of Fe oxides. These alternating periods of reduction and oxidation, correlated to the alternating dry and wet cycles within the soil, are therefore responsible for the segregation and redistribution of Fe oxides resulting in zones of relative iron accumulations and depletions (Peterschmitt et al. 1996; Rabenhorst & Parikh 2000). These zones are easily identifiable based on the distinct colours they display (Vepraskas 1992). Iron depletion zones are generally the colour of uncoated mineral grains (i.e. bleached, low chroma, grey to white colours) whilst Fe accumulation zones are redder or browner chromatic sections.

Although clay eluviation has been proposed as a potential mechanism responsible for bleached topsoil colourations, no certainty exists about what the mechanism is with which the translocation of clay

particles causes a loss in colour. The process by which fine soil material moves out of a horizon or soil zone is referred to as eluviation (IUSS working group WRB 2007; Cornu et al. 2014). The release and mobilisation of these colloidal particles are dictated by electrostatic charge balances. In simple terms, for the negatively charged clay colloids to be transported through the soil medium, either repulsive forces by other negatively charged soil constituents or attractive forces binding the particles to a positively charged mobile substance must be present in the immediate soil environment. Various other soil features can however alter the direction and extent of the electrostatic influence of a particular soil constituent. Therefore, any electrostatically active soil component or feature responsible for changes in the electrostatic charge balance of the soil environment can influence clay dispersibility.

Amézketa (1999) lists electrolyte concentration (EC), solution pH, sodium adsorption ratio, clay mineralogy,  $\text{CaCO}_3$ , gypsum, organic matter and sesquioxides as internal soil features applicable to clay dispersion. Sesquioxides, and more particularly Fe oxides, are of great interest in this study due to their abundance in the sampled soils and their known stabilising effect on the soil colloidal fraction (Duiker et al. 2003). One of the hypotheses proposed to explain eluviation-related bleaching in the Western Cape in particular, is associated with the crystallinity and therefore reactivity of the present Fe oxide phases. It is proposed that due to the mature age of the landscape and its soils (Hendey 1983), the present Fe oxides will be extremely crystalline and therefore less reactive and capable of stabilising the clay phase (Bech et al. 1997; Duiker et al. 2003). In addition, Laker (2004) also considers parent material, the degree of soil weathering and pedogenesis, magnesium, and particle size distribution as additional factors influential to dispersive soils in South Africa.

The aim of this chapter was to chemically and physically characterise bleached topsoils and the weakly structured subsoil horizons they overlie and to use this information to determine whether Fe reduction, clay eluviation or any other mechanism could in fact be responsible for bleaching in these soil profiles. In addition, although all the sampled profiles were collectively investigated, bleached and non-bleached profiles from the two sampling regions were also separately assessed to determine whether the actual mechanisms responsible for bleaching under these weakly-structured subsoil conditions were the same across the Western Cape Province and Mpumalanga Highveld of South Africa.

## 4.2 MATERIALS AND METHODS

Soil sampling, colour measurement and physical and chemical soil characterisation was completed following the methods specified in Chapter 2.

### 4.2.1 *Statistical analyses*

For all the determined physical and chemical soil characteristics, descriptive statistical parameters including the range, mean and standard deviation (SD) were calculated. Significance testing was conducted by means of a combination of one-way and two-way ANOVAs to be able to identify which features differed between soils from 1) the Western Cape (WC) and Mpumalanga Highveld, 2) bleached and non-bleached profiles, and more specifically also 3) the bleached and non-bleached profiles in each location. Differences were deemed to be significant at p-values < 0.05 whilst trends were also reported up to p-values of  $\leq 0.15$ . The decision to report on such trends was based upon the small data set that was analysed in the study and the awareness that each profile represents a complex amalgamation of pedogenic processes and therefore does not serve as a true statistical replicate of a particular morphology.

Although significance testing was conducted on the soil profile groupings of both measured and perceived colours, measured colour groupings are predominantly reported due to the higher precision level of the instrument (Post et al. 1993).

In addition, a Principle Component Analysis (PCA) was conducted on the determined soil parameters to indicate which soil characteristics show variation between bleached and non-bleached soil profiles. The profiles were grouped into bleached or non-bleached based on measured soil colours and a PCA biplot was generated for all the sampled profiles combined as well as separately per location. This was done to ensure that if different soil parameters had different influences in each of the two locations, this would be visually represented in the location-specific biplots.

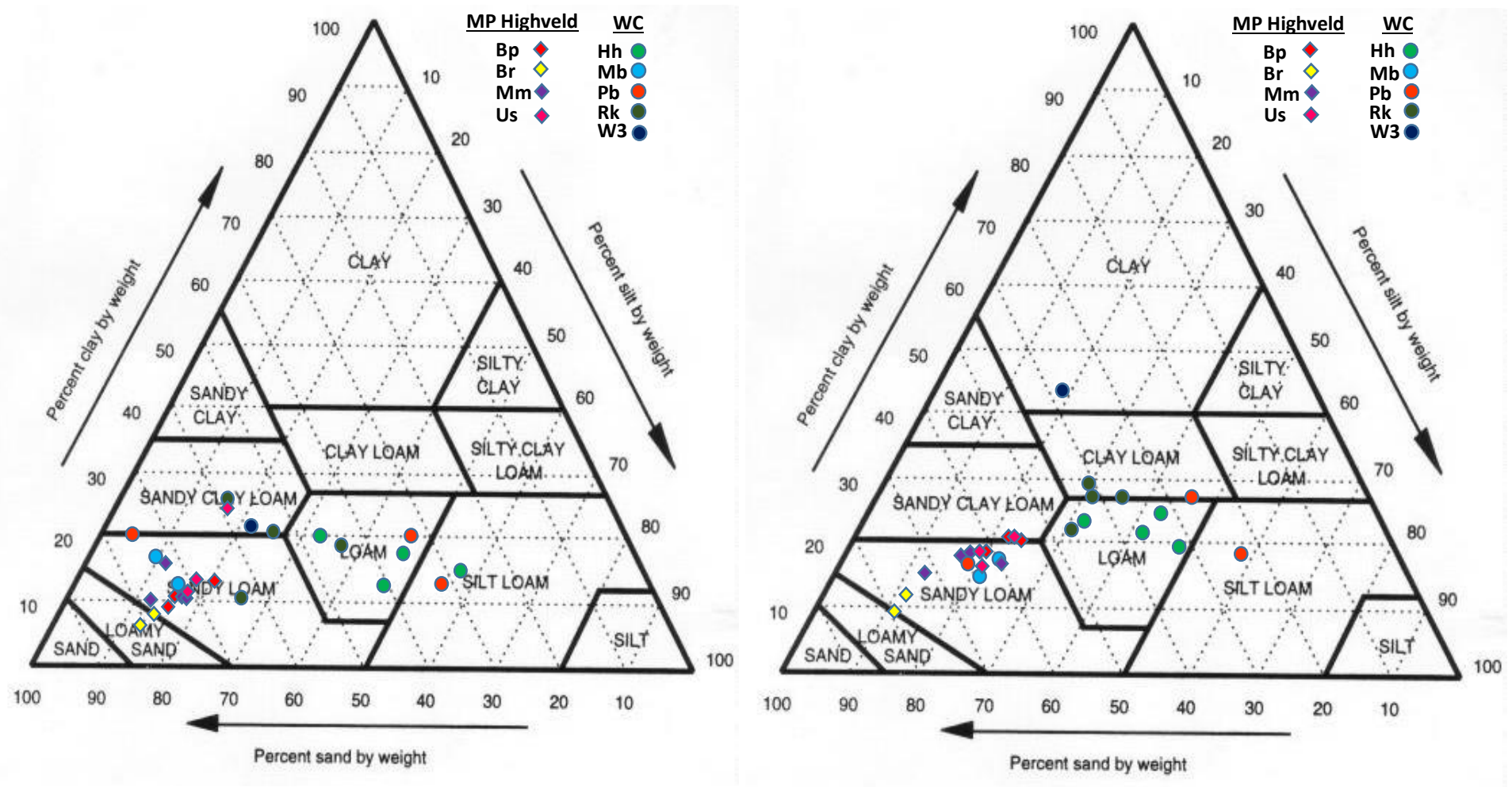
## 4.3 RESULTS AND DISCUSSION

### 4.3.1 *Physical soil characterisation*

#### 4.3.1.1 *Particle size distribution*

Distinct differences in the particle size distributions of the soil profiles sampled on the Mpumalanga Highveld and Western Cape were observed. The different size class distributions are presented in more detail in Appendix 4.1. The Western Cape profiles had a significantly greater silt and clay content in both the top- and subsoil compared to the Highveld profiles which were subsequently more sandy (Figures 4.1a & b). As a result the majority of the Highveld soils had a sandy loam texture whilst the

greater fine soil fractions in the Western Cape profiles meant that silt-, clay- and true loam soils were more abundant. There were no significant differences in the particle size distributions of bleached and non-bleached profiles on the Highveld whilst in the Western Cape both the top- and subsoil horizons of the sampled bleached profiles had significantly greater silt contents and consequently lower clay contents than the non-bleached variants. Clay change parameters indicating the difference in the fine and coarse clay fractions between the sub- and topsoil horizons indicated differences in the proportional distribution of these size fractions in the Western Cape soils. Although this feature will be discussed in more detail in the subsequent section on the dispersible clay phases of these soils, these clay changes indicated that bleached profiles in the Western Cape have proportionally more Fi clay in the subsoil than in the topsoil compared to the non-bleached variants.



#### 4.3.1.2 Bulk density

The determined bulk densities (BD) of the sampled soils did not exhibit any substantial differences between bleached and non-bleached profiles in either of the two locations. Bulk density in general seemed to be quite variable and very high, exceeding values of  $1900 \text{ kg.m}^{-3}$  in some instances (Table 4.1). This was attributed to erroneous sampling and experimental approaches, where bulk density was determined using the clod method on weakly structured soils that exhibited limited levels of aggregation. The result being that many of the collected clods were friable and weak and of variable size which affected the generated results. What was however noticeable was that the topsoil bulk density was significantly higher in the cultivated Highveld soils than in the undisturbed Western Cape profiles ( $F=6.9$ ,  $p=0.02$ ). Although conventional tillage practices are applied on the maize fields where these soils were sampled and thus it would be expected that topsoil bulk density should be lower in these areas (Franzluebbers et al. 1995; Osunbitan et al. 2005), it is proposed that the higher bulk densities in the Highveld is a consequence of soil texture and/or the sampling approach that was followed. When sampling weak structured soils with minimal macro-aggregation the risk is that upon removing the clod from the profile, all the loosened soil crumbles away and essentially the most compact parts of the profile i.e. clods are removed and used to determine bulk density. Furthermore, Daddow & Warrington (1983) also concluded that coarse-textured soils have greater bulk densities than fine-textured variants. The reported sandier textures of the Highveld soils can therefore also be the cause of the higher bulk densities reported in this location. Nonetheless, bulk density results are often proven to be variable (Ferrerias et al. 2000) and for the purpose of this study, it was deemed to have no relation to bleaching in either of the two locations.

**Table 4.1.** Top- and subsoil bulk density. The value range, mean and standard deviation (SD) for the sampled top- and subsoil horizons at each location is given.

	Western Cape				Mpumalanga Highveld			
	Bleached		Non-bleached		Bleached		Non-bleached	
	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD
Topsoil bulk density ( $\text{kg.m}^{-3}$ )	1183-1885	<b>1560</b> $\pm$ 234	1492-1859	<b>1631.9</b> $\pm$ 131.2	1585-1907	<b>1729</b> $\pm$ 125	1635-1949	<b>1797</b> $\pm$ 109
Subsoil bulk density ( $\text{kg.m}^{-3}$ )	1518-1790	<b>1668</b> $\pm$ 102	1527-1799	<b>1709</b> $\pm$ 97	1487-1918	<b>1690</b> $\pm$ 206	1490-1938	<b>1650</b> $\pm$ 158



#### 4.3.1.3 Water dispersible clay (WDC)

From the values presented in Table 4.2, both the top- and subsoil horizons of the Western Cape profiles had an observable greater WDC % than the soils from the Highveld. The results generated by means of ANOVA analyses concluded these differences to be significant for both horizons (Table 4.3). The topsoil WDC % also tended to be higher in bleached compared to non-bleached profiles collectively, but the consequent two-way ANOVAs that were performed proved this trend to be the result of the significantly higher WDC % in bleached Western Cape profiles compared to the non-bleached variants of this location (Table 4.3, Figure 4.2). There was no significant difference between the water dispersible clay phase of bleached and non-bleached topsoils on the Mpumalanga Highveld. Although the difference was less pronounced, the subsoil WDC % proved to follow a similar trend being higher in the bleached compared to non-bleached soils of the Western Cape and showing no difference on the Mpumalanga Highveld (Figure 4.2).

**Table 4.2.** Clay dispersion parameters. The water dispersible clay (WDC) percentages of the top- and subsoil horizons and the percentage clay increase from the A to the B horizon for the different clay fractions. The value range as well as the mean and standard deviation (SD) for each variable is given.

	Western Cape				Mpumalanga Highveld			
	Bleached		Non-bleached		Bleached		Non-bleached	
	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD
<i>Topsoil WDC (%)</i> <sup>1</sup>	15.5-59.9	<b>38.0</b> $\pm$ 15.4	12.2-35.2	<b>24.4</b> $\pm$ 8.6	1.7-11.2	<b>8.0</b> $\pm$ 3.8	7.2-13.3	<b>10.3</b> $\pm$ 2.3
<i>Subsoil WDC (%)</i> <sup>1</sup>	8.5-57.4	<b>28.0</b> $\pm$ 18.9	2.0-30.4	<b>18.5</b> $\pm$ 9.0	8.0-14.9	<b>10.8</b> $\pm$ 2.7	2.8-22.0	<b>9.4</b> $\pm$ 6.2
<i>Total clay change (%)</i> <sup>2</sup>	5.0-139.9	<b>42.4</b> $\pm$ 45.8	15.0-89.0	<b>47.0</b> $\pm$ 30.3	8.4-50.1	<b>28.8</b> $\pm$ 18.9	-26.9-44.4	<b>15.6</b> $\pm$ 24.0
<i>Co clay change (%)</i> <sup>2</sup>	2.1-114.8	<b>35.7</b> $\pm$ 37.5	14.9-78.5	<b>36.5</b> $\pm$ 22.9	8.8-47.1	<b>25.7</b> $\pm$ 17.4	-26.7-41.7	<b>14.1</b> $\pm$ 23.8
<i>Fi clay change (%)</i> <sup>2</sup>	9.4-3901.6	<b>969.8</b> $\pm$ 1375.3	9.1-511.1	<b>128.7</b> $\pm$ 191.2	5.0-83.0	<b>47.5</b> $\pm$ 29.7	-27.9-58.2	<b>24.6</b> $\pm$ 26.1

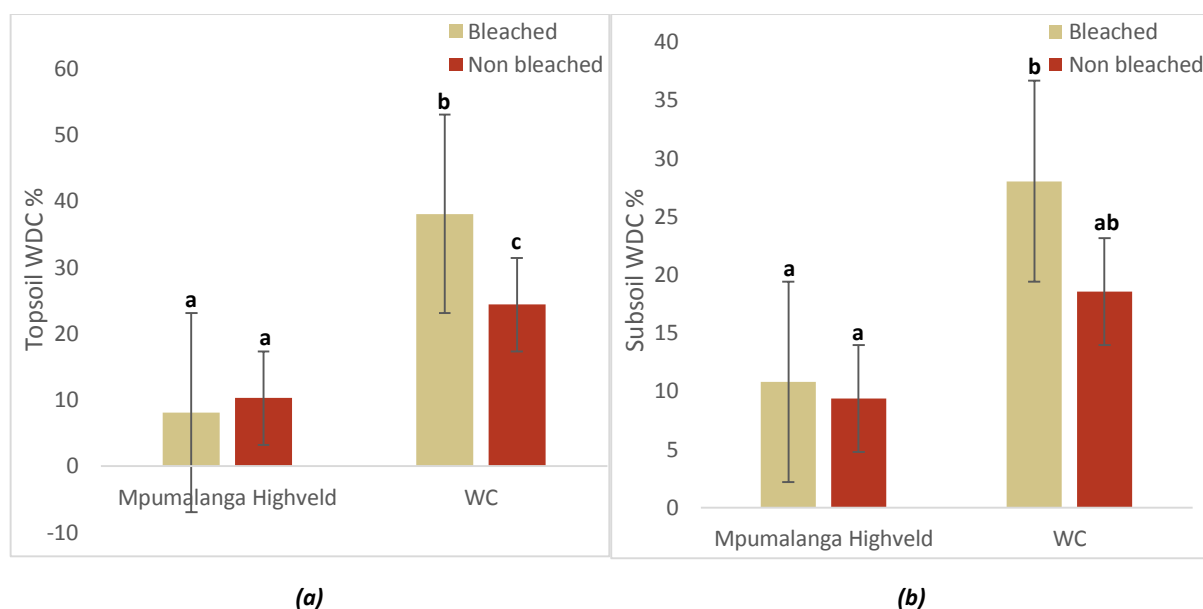
<sup>1</sup> **WDC %** = [Water dispersible clay fraction (% of total clay) / Sodium dispersible clay fraction (% of total clay)] \* 100

<sup>2</sup> **Clay change %** = [(Clay % horizon 2 – Clay % horizon 1) / Clay % horizon 1] \* 100

**Table 4.3.** Comparison between the water dispersible clay percentages of the sampled top- and subsoil horizons by means of one-way and two-way ANOVAs.

Grouping variables	F-value	p-value
<b>Topsoil WDC (%)</b>		
WC vs MP Highveld	34.66	<0.01*
Bleached vs Non-bleached	2.34	0.14*
WC: Bleached vs Non-bleached	4.51	0.01*
MP Highveld: Bleached vs Non-bleached	4.51	0.69
<b>Subsoil WDC (%)</b>		
WC vs MP Highveld	8.46	<0.01*
Bleached vs Non-bleached	1.44	0.24
WC: Bleached vs Non-bleached	0.79	0.14*
MP Highveld: Bleached vs Non-bleached	0.79	0.83

(\* = significant differences &amp; reported trends)

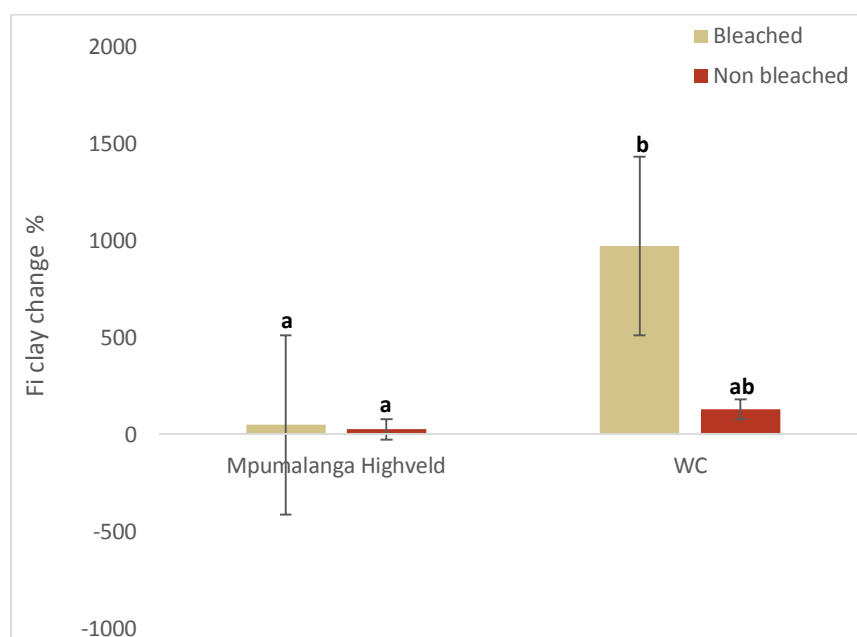
**Figure 4.2.** The difference between the topsoil (a) and subsoil (b) WDC % of bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

To substantiate the WDC results which clearly suggested the Western Cape profiles to be more dispersive, clay change parameters were also calculated from the particle size distribution data. This was done separately for each clay fraction and entailed expressing the difference in clay content from the first to the second horizon as a percentage of the first horizon's total clay fraction. Although less apparent from the values given in Table 4.2, the ANOVA analyses suggested similar trends as with the WDC %. Total-, coarse- and fine clay tended to increase towards the subsoil horizons in the Western Cape profiles, whereas no such trends were observed in the Highveld soils. With regards to bleaching, fine clay change tended to be higher in bleached compared to non-bleached profiles but this was again attributed to the strong trend reported in fine clay change between Western Cape bleached and non-bleached soils (Table 4.4, Figure 4.3).

**Table 4.4.** Comparison of the changes in the different clay fractions from the first to the second horizon of the sampled soil profiles by means of one-way and two-way ANOVAs.

Grouping variables	F-value	p-value
<b>Total clay change (%)</b>		
WC vs MP Highveld	3.08	0.09*
Bleached vs Non-bleached	0.11	0.74
WC: Bleached vs Non-bleached	0.48	0.79
MP Highveld: Bleached vs Non-bleached	0.48	0.49
<b>Coarse clay change (%)</b>		
WC vs MP Highveld	2.15	0.16*
Bleached vs Non-bleached	0.24	0.63
WC: Bleached vs Non-bleached	0.32	0.95
MP Highveld: Bleached vs Non-bleached	0.32	0.47
<b>Fine clay change (%)</b>		
WC vs MP Highveld	2.94	0.10*
Bleached vs Non-bleached	2.08	0.16*
WC: Bleached vs Non-bleached	1.87	0.05*
MP Highveld: Bleached vs Non-bleached	1.87	0.96

(\* = significant differences &amp; reported trends)

**Figure 4.3.** The difference between the fine clay change % of the bleached and non-bleached Western Cape and Highveld profiles. Standard error bars and significance letters are indicated.

Although the fine clay change does not give an absolute indication of clay translocation, it is presumed that if clay was being transported by percolating water through these profiles, the finest clay fraction would most likely be subject to mobilisation (Chittleborough 1992; Fey 2010). Therefore, the results obtained from the calculated fi clay change percentages are regarded as evidence in support of a dispersive clay phase and potentially also clay movement from the A to the B horizons of the sampled profiles.

### 4.3.2 Chemical soil characterisation

#### 4.3.2.1 pH & EC

**Table 4.5.** The pH and electrical conductivity (EC) (mS/m). The value range as well as the mean and standard deviation (SD) for each variable is given.

	Western Cape				Mpumalanga Highveld			
	Bleached		Non-bleached		Bleached		Non-bleached	
	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD
Topsoil pH (H <sub>2</sub> O)	4.8-6.2	<b>5.5</b> $\pm$ 0.5	5.0-5.8	<b>5.5</b> $\pm$ 0.4	5.5-7.0	<b>6.1</b> $\pm$ 0.6	5.1-6.3	<b>5.6</b> $\pm$ 0.4
Topsoil pH (KCl)	3.8-5.2	<b>4.5</b> $\pm$ 0.6	3.8-5.0	<b>4.4</b> $\pm$ 0.4	4.2-6.2	<b>5.1</b> $\pm$ 0.8	4.3-5.3	<b>4.6</b> $\pm$ 0.3
Subsoil pH (H <sub>2</sub> O)	4.7-6.2	<b>5.4</b> $\pm$ 0.6	5.1-6.5	<b>5.7</b> $\pm$ 0.7	5.0-7.2	<b>6.0</b> $\pm$ 0.9	4.9-6.3	<b>5.6</b> $\pm$ 0.7
Subsoil pH (KCl)	3.8-4.9	<b>4.3</b> $\pm$ 0.4	4.0-5.5	<b>4.4</b> $\pm$ 0.5	4.2-6.3	<b>5.0</b> $\pm$ 0.9	4.2-5.6	<b>4.7</b> $\pm$ 0.6
Topsoil EC (mS/m)	1.7-15.7	<b>8.6</b> $\pm$ 4.8	1.6-19.1	<b>11.2</b> $\pm$ 6.5	1.3-13.2	<b>7.1</b> $\pm$ 5.8	1.5-15.4	<b>8.9</b> $\pm$ 4.4
Subsoil EC (mS/m)	1.6-8.3	<b>4.0</b> $\pm$ 3.0	1.2-44.1	<b>9.6</b> $\pm$ 15.7	1.1-9.7	<b>6.8</b> $\pm$ 3.5	1.1-14.7	<b>7.7</b> $\pm$ 5.2

The basic soil chemical properties of pH and electrical conductivity (EC) proved to have no observable relation to the occurrence of bleaching. According to Table 4.5, the topsoil pH in water ranged from 4.8 to 6.2 in the Western Cape and 5.1 to 7.0 on the Highveld. The topsoil pH in KCl was, as expected, lower and ranged from 3.8 to 5.2 in the Western Cape and 4.2 to 6.2 on the Highveld. Subsoil pH in water proved to be fairly similar to the recorded topsoil values and ranged from 4.7-6.5 and 4.9-7.2 in the Western Cape and Mpumalanga Highveld respectively. Subsoil pH in KCl in the Western Cape was between 3.8 and 5.5 and in the Highveld between 4.2 and 6.3. The pH measurements in KCl eluded to the presence of moderate levels of reserve acidity on the exchange sites of the soils at both locations. Significance testing recorded a strong trend suggesting topsoil pH in both water ( $p=0.13$ ) and KCl ( $p=0.07$ ) to be higher for the Highveld soils compared to those of the Western Cape. The subsoil pH values followed a similar, but less pronounced trend.

In general, the overall lower pH values reported for these red and yellow weakly structured soils across the different areas of their distribution are not unexpected seeing that these soils are known to be highly leached (Lambrechts 1983; Fey 2010). The reported higher pH values on the Mpumalanga Highveld is most probably the result of lime additions in the maize fields where these soils were sampled. The influence of natural fynbos vegetation can also be the cause for the slightly more acidic pH values that were recorded at the Western Cape sites (Richards et al. 1997). No significant trends

were observed for the measured EC between the two locations or between the bleached and non-bleached profiles in either.

#### **4.3.2.2**     *Exchangeable cations*

The ECEC of the sampled top- and subsoil horizons were relatively low (Table 4.6) but did not prove to be substantially different between the two locations nor between the bleached and non-bleached profiles in each. Base saturation percentages indicated that on average, high saturation levels (Table 4.6) were present in the soils at both locations although base saturation on the Highveld was significantly higher compared to the Western Cape in both topsoil ( $p=0.03$ ) and subsoil ( $p=0.05$ ) horizons. No difference was recorded between bleached and non-bleached profiles collectively or separately per location. As can be expected from the lower pH values, the titrated exchangeable acidity was significantly higher in the top- ( $p=0.02$ ) and subsoil horizons ( $p=0.02$ ) of the Western Cape.

The topsoil ESP values showed that the Western Cape soils contained significantly more Na on their exchange sites (Table 4.7, Figure 4.4a) although the ESP levels of these Western Cape topsoils still reflect only marginal- to non-sodic conditions (Hazelton & Murphy 2007). Subsoil ESP followed a similar trend (Table 4.7, Figure 4.4b) with the recorded ESP values also being within comparable ranges to that recorded for the topsoil horizons (Table 4.6). Noticeably, the overall top-and subsoil ESP did not significantly differ between bleached and non-bleached profiles nor between the bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld respectively (Table 4.7). The topsoil Ca:Mg ratio tended to be higher in the Highveld profiles with this trend being less pronounced in the subsoil, but still observable (Table 4.7, Figure 4.5a). Essentially, a high Ca to Mg ratio indicates that the divalent Ca cation, which is a very effective clay flocculent, is present in sufficient quantities relative to Mg to overcome the dispersing effect that Mg has on soil colloids, especially in soils with high sodium saturation levels (Bakker & Emerson 1973; Curtin et al. 1994; Dontsova & Norton 2001). As with the ESP, no differences between bleached and non-bleached profiles collectively or individually per region were observed (Table 2.8).

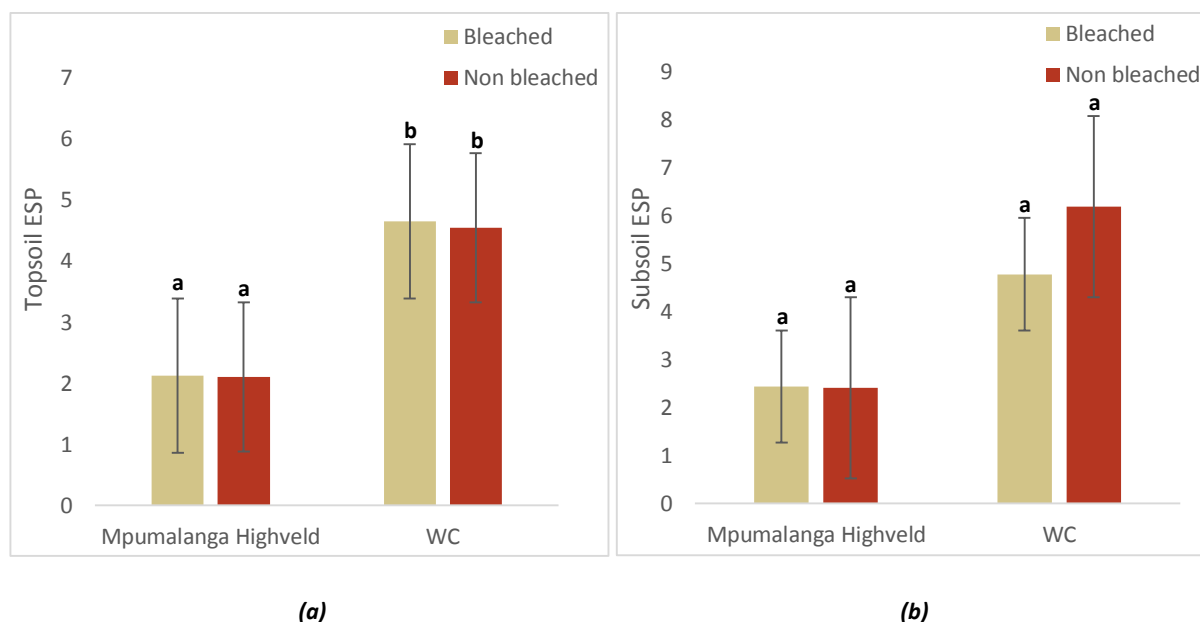
**Table 4.6.** Exchangeable soil cations in  $\text{cmol}_c.\text{kg}^{-1}$  determined at soil pH together with calculated standard cation parameters. The value range as well as the mean and standard deviation (SD) for each variable is given.

	Western Cape				Mpumalanga Highveld			
	Bleached		Non-bleached		Bleached		Non-bleached	
	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD
<i>Topsoil</i>								
<i>Ca (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.37-2.80	<b>1.18</b> $\pm$ 0.85	0.17-3.50	<b>1.54</b> $\pm$ 1.05	0.70-2.95	<b>1.92</b> $\pm$ 0.85	0.88-2.69	<b>1.63</b> $\pm$ 0.57
<i>Mg (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.33-1.72	<b>0.75</b> $\pm$ 0.51	0.30-1.32	<b>0.74</b> $\pm$ 0.34	0.47-0.92	<b>0.60</b> $\pm$ 0.12	0.28-1.32	<b>0.6</b> $\pm$ 0.34
<i>K (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.12-0.42	<b>0.29</b> $\pm$ 0.12	0.08-0.28	<b>0.13</b> $\pm$ 0.07	0.14-0.44	<b>0.29</b> $\pm$ 0.12	0.13-0.38	<b>0.28</b> $\pm$ 0.09
<i>Na (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.10-0.30	<b>0.14</b> $\pm$ 0.07	0.13-0.94	<b>0.40</b> $\pm$ 0.27	0.05-0.07	<b>0.06</b> $\pm$ 0.01	0.04-0.07	<b>0.06</b> $\pm$ 0.01
<i>S-value (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	1.13-5.05	<b>2.36</b> $\pm$ 1.34	1.34-5.85	<b>2.80</b> $\pm$ 1.52	1.42-4.18	<b>2.87</b> $\pm$ 1.01	1.68-3.77	<b>2.62</b> $\pm$ 0.80
<i>Exchangeable Al (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.00-1.40	<b>0.59</b> $\pm$ 0.64	0.09-0.98	<b>0.33</b> $\pm$ 0.32	0.00-0.25	<b>0.10</b> $\pm$ 0.10	0.00-0.25	<b>0.14</b> $\pm$ 0.10
<i>Exchangeable acidity (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.02-1.84	<b>0.80</b> $\pm$ 0.82	0.09-1.44	<b>0.51</b> $\pm$ 0.50	0.02-0.34	<b>0.14</b> $\pm$ 0.13	0.04-0.34	<b>0.18</b> $\pm$ 0.10
<i>ECEC (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	2.20-5.09	<b>3.15</b> $\pm$ 0.95	2.33-5.94	<b>3.31</b> $\pm$ 1.24	1.76-4.19	<b>3.01</b> $\pm$ 0.89	1.92-3.82	<b>2.80</b> $\pm$ 0.73
<i>Base saturation %</i>	38.7-99.3	<b>73.3</b> $\pm$ 26.3	48.2-98.5	<b>81.8</b> $\pm$ 18.7	80.6-99.6	<b>93.8</b> $\pm$ 7.8	86.9-98.9	<b>92.5</b> $\pm$ 4.7
<i>ESP</i>	2.16-8.47	<b>4.65</b> $\pm$ 1.97	1.46-10.45	<b>4.54</b> $\pm$ 2.98	1.56-3.45	<b>2.12</b> $\pm$ 0.76	1.25-2.95	<b>2.10</b> $\pm$ 0.58
<i>Ca:Mg</i>	0.53-3.60	<b>1.80</b> $\pm$ 1.15	0.28-4.18	<b>2.21</b> $\pm$ 1.29	1.49-4.44	<b>3.15</b> $\pm$ 1.25	1.50-5.57	<b>2.97</b> $\pm$ 1.51
<i>Subsoil</i>								
<i>Ca (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.10-2.73	<b>0.81</b> $\pm$ 0.92	0.07-1.77	<b>0.97</b> $\pm$ 0.55	0.57-2.36	<b>1.43</b> $\pm$ 0.73	0.40-2.40	<b>1.30</b> $\pm$ 0.76
<i>Mg (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.08-1.23	<b>0.67</b> $\pm$ 0.39	0.35-2.71	<b>1.02</b> $\pm$ 0.83	0.39-0.85	<b>0.65</b> $\pm$ 0.21	0.13-1.30	<b>0.62</b> $\pm$ 0.35
<i>K (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.07-0.43	<b>0.24</b> $\pm$ 0.13	0.07-0.69	<b>0.28</b> $\pm$ 0.22	0.08-0.22	<b>0.14</b> $\pm$ 0.06	0.07-0.20	<b>0.15</b> $\pm$ 0.04
<i>Na (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.08-0.23	<b>0.13</b> $\pm$ 0.05	0.07-0.70	<b>0.20</b> $\pm$ 0.23	0.05-0.08	<b>0.06</b> $\pm$ 0.01	0.05-0.07	<b>0.06</b> $\pm$ 0.01
<i>S-value (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.33-4.36	<b>1.84</b> $\pm$ 1.30	1.07-4.04	<b>2.48</b> $\pm$ 0.96	1.12-3.33	<b>2.28</b> $\pm$ 0.87	1.11-3.26	<b>2.13</b> $\pm$ 0.72
<i>Exchangeable Al (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.08-1.60	<b>0.69</b> $\pm$ 0.64	0.02-1.40	<b>0.56</b> $\pm$ 0.49	0.00-0.43	<b>0.16</b> $\pm$ 0.18	0.00-0.65	<b>0.27</b> $\pm$ 0.26
<i>Exchangeable acidity (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	0.04-2.09	<b>0.90</b> $\pm$ 0.82	0.02-1.84	<b>0.80</b> $\pm$ 0.63	0.02-0.64	<b>0.24</b> $\pm$ 0.27	0.02-0.79	<b>0.33</b> $\pm$ 0.32
<i>ECEC (cmol<sub>c</sub>.kg<sup>-1</sup>)</i>	1.48-4.40	<b>2.74</b> $\pm$ 0.95	2.41- 4.28	<b>3.27</b> $\pm$ 0.58	1.51-3.34	<b>2.52</b> $\pm$ 0.68	1.55-3.30	<b>2.46</b> $\pm$ 0.56
<i>Base saturation %</i>	99.1-22.7	<b>63.9</b> $\pm$ 31.6	44.3-99.4	<b>74.2</b> $\pm$ 21.5	73.6-99.5	<b>88.1</b> $\pm$ 13.2	64.7-99.3	<b>85.1</b> $\pm$ 14.3
<i>ESP</i>	3.42-7.56	<b>4.78</b> $\pm$ 1.43	2.51-22.27	<b>6.19</b> $\pm$ 7.16	1.67-3.64	<b>2.43</b> $\pm$ 0.85	1.95-3.65	<b>2.41</b> $\pm$ 0.57
<i>Ca:Mg</i>	0.19-2.63	<b>1.21</b> $\pm$ 0.91	0.13-2.96	<b>1.39</b> $\pm$ 1.12	0.95-3.41	<b>2.27</b> $\pm$ 1.11	0.56-15.35	<b>3.84</b> $\pm$ 5.23

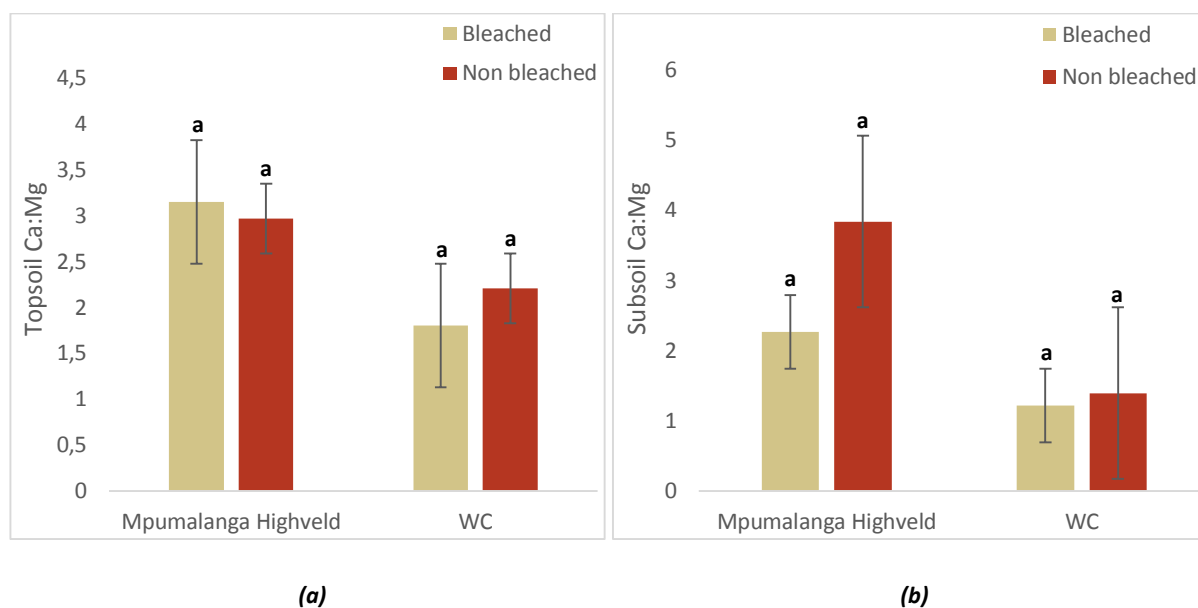
**Table 4.7.** The calculated exchangeable sodium percentage (ESP) and Ca:Mg ratio of the sampled top- and subsoil horizons by means of one-way and two-way ANOVAs.

Grouping variables	F-value	p-value
<b>Topsoil ESP</b>		
WC vs MP Highveld	10.67	<0.01*
Bleached vs Non-bleached	0.01	0.94
WC: Bleached vs Non-bleached	0.00	0.92
MP Highveld: Bleached vs Non-bleached	0.00	0.99
<b>Subsoil ESP</b>		
WC vs MP Highveld	4.03	0.06*
Bleached vs Non-bleached	0.21	0.65
WC: Bleached vs Non-bleached	0.22	0.50
MP Highveld: Bleached vs Non-bleached	0.22	0.99
<b>Topsoil Ca:Mg</b>		
WC vs MP Highveld	4.10	0.06*
Bleached vs Non-bleached	0.05	0.83
WC: Bleached vs Non-bleached	0.31	0.57
MP Highveld: Bleached vs Non-bleached	0.31	0.82
<b>Subsoil Ca:Mg</b>		
WC vs MP Highveld	2.35	0.14*
Bleached vs Non-bleached	0.59	0.45
WC: Bleached vs Non-bleached	0.37	0.36
MP Highveld: Bleached vs Non-bleached	0.37	0.91

(\* = significant differences &amp; reported trends)

**Figure 4.4.** The calculated exchangeable sodium percentage (ESP) of the sampled top- (a) and subsoil (b) horizons of bleached and non-bleached profiles in both the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.





**Figure 4.5.** The calculated Calcium to Magnesium ratio of the sampled top- **(a)** and subsoil **(b)** horizons of bleached and non-bleached profiles in both the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

From the results obtained during the exchangeable cation analyses it is presumed that the higher ESP values reported for the Western Cape profiles together with the lower Ca:Mg ratio contributed to the very dispersive clay phase that was recorded in these soils (Amézketa 1999; Laker 2004). In addition, the higher base saturation and lower exchangeable acidity levels in the Highveld is most probably a consequence of the fertilisation program applied to the maize fields in which these soils were sampled.

#### 4.3.2.3 Extractable Fe & Al

Due to the different Fe and Al phases that are targeted by the citrate-bicarbonate-dithionite (CBD) and ammonium oxalate (AAO) extraction agents, the registered  $Fe_{CBD}$  and  $Al_{CBD}$  content in the soil differs from the  $Fe_{AAO}$  and  $Al_{AAO}$  values. Although some controversy exists regarding these extraction processes, particularly with regards to Al oxides, CBD is deemed to be a stronger reducing agent which targets both crystalline and poorly-crystalline Fe oxide phases whereas AAO is deemed to extract only the poorly crystalline and very reactive Fe oxide phases (McKeague & Day 1966; Loeppert & Inskeep 1996). The  $Fe_{CBD}$  content is subsequently also used as a representation of the total Fe oxide content of the soils. Seeing that the above described functioning of the two reducing agents is more assured for Fe oxides compared to Al, no assumptions were made about the crystallinity of the Al phases present within the soils. From the determined Fe contents however, a crystallinity index (CI) quantifying the crystalline nature of the recorded Fe oxides was calculated as indicated in Table 4.8. In the study by Bech et al. (1997) a similar ratio was calculated, which was referred to as the Fe activity ratio. The nomenclature in this study was based on the relationship between crystallinity and reactivity (Duiker et al. 2003).

**Table 4.8.** The extracted citrate-bicarbonate-dithionite (CBD) and acidified ammonium oxalate (AAO) Fe and Al fractions from the sampled top-and subsoil horizons. The calculated crystallinity index (CI) of the soil Fe content, an Al ratio and the soil Fe: clay ratio is also presented. The value range as well as the mean and standard deviation (SD) for each variable is given.

	Western Cape				Mpumalanga Highveld			
	Bleached		Non-bleached		Bleached		Non-bleached	
	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD
<i>Topsoil</i>								
$Fe_{CBD}$ (%)	2.78-0.56	<b>1.61</b> $\pm$ 0.82	1.16-2.55	<b>1.73</b> $\pm$ 0.48	0.67-1.88	<b>1.23</b> $\pm$ 0.44	1.05-2.39	<b>1.52</b> $\pm$ 0.45
$Fe_{AAO}$ (%)	0.08-0.15	<b>0.11</b> $\pm$ 0.03	0.09-0.17	<b>0.12</b> $\pm$ 0.03	0.07-0.11	<b>0.10</b> $\pm$ 0.02	0.08-0.13	<b>0.10</b> $\pm$ 0.02
$Fe$ CI (%) <sup>1</sup>	4.96-15.14	<b>8.36</b> $\pm$ 3.57	4.47-9.92	<b>7.46</b> $\pm$ 1.79	5.76-10.83	<b>8.34</b> $\pm$ 1.94	5.27-7.43	<b>6.53</b> $\pm$ 0.87
$Al_{CBD}$ (%)	0.15-0.61	<b>0.29</b> $\pm$ 0.17	0.10-0.41	<b>0.28</b> $\pm$ 0.12	0.11-0.25	<b>0.18</b> $\pm$ 0.06	0.16-0.34	<b>0.24</b> $\pm$ 0.06
$Al_{AAO}$ (%)	0.07-0.27	<b>0.14</b> $\pm$ 0.07	0.07-0.16	<b>0.12</b> $\pm$ 0.03	0.09-0.13	<b>0.11</b> $\pm$ 0.02	0.10-0.21	<b>0.13</b> $\pm$ 0.04
$Al$ ratio (%) <sup>2</sup>	34.33-60.0	<b>48.37</b> $\pm$ 7.99	24.64-70.59	<b>49.23</b> $\pm$ 14.99	46.15-91.67	<b>66.90</b> $\pm$ 19.50	41.07-102.94	<b>57.56</b> $\pm$ 21.31
$Fe_{CBD}$ :clay	0.09-0.17	<b>0.12</b> $\pm$ 0.03	0.10-0.19	<b>0.14</b> $\pm$ 0.03	0.11-0.19	<b>0.13</b> $\pm$ 0.03	0.09-0.18	<b>0.13</b> $\pm$ 0.03
<i>Subsoil</i>								
$Fe_{CBD}$ (%)	1.08-2.54	<b>1.86</b> $\pm$ 0.63	1.50-4.58	<b>2.86</b> $\pm$ 1.03	0.61-2.02	<b>1.40</b> $\pm$ 0.50	1.44-3.24	<b>2.23</b> $\pm$ 0.80
$Fe_{AAO}$ (%)	0.08-0.19	<b>0.13</b> $\pm$ 0.04	0.11-0.35	<b>0.20</b> $\pm$ 0.09	0.07-0.16	<b>0.11</b> $\pm$ 0.03	0.08-0.16	<b>0.11</b> $\pm$ 0.03
$Fe$ CI (%) <sup>1</sup>	4.26-11.49	<b>7.32</b> $\pm$ 2.32	3.57-12.75	<b>7.58</b> $\pm$ 3.29	5.66-11.80	<b>8.14</b> $\pm$ 2.78	2.50-9.39	<b>5.61</b> $\pm$ 2.28
$Al_{CBD}$ (%)	0.21-0.59	<b>0.35</b> $\pm$ 0.13	0.10-0.72	<b>0.43</b> $\pm$ 0.10	0.11-0.35	<b>0.26</b> $\pm$ 0.09	0.13-0.46	<b>0.30</b> $\pm$ 0.11
$Al_{AAO}$ (%)	0.10-0.28	<b>0.16</b> $\pm$ 0.06	0.09-0.24	<b>0.17</b> $\pm$ 0.05	0.08-0.17	<b>0.14</b> $\pm$ 0.04	0.10-0.25	<b>0.16</b> $\pm$ 0.05
$Al$ ratio (%) <sup>2</sup>	31.15-62.79	<b>45.91</b> $\pm$ 9.37	22.50-93.75	<b>48.87</b> $\pm$ 23.52	46.51-73.68	<b>56.18</b> $\pm$ 11.62	27.63-95.45	<b>59.71</b> $\pm$ 27.23
$Fe_{CBD}$ :clay	0.06-0.16	<b>0.11</b> $\pm$ 0.04	0.08-0.19	<b>0.12</b> $\pm$ 0.03	0.10-0.15	<b>0.12</b> $\pm$ 0.02	0.09-0.26	<b>0.16</b> $\pm$ 0.06

<sup>1</sup> Fe CI (%): [ $Fe_{AAO}$  (mg.kg<sup>-1</sup>) /  $Fe_{CBD}$  (mg.kg<sup>-1</sup>)] \* 100

<sup>2</sup> Al ratio: [ $Al_{AAO}$  (mg.kg<sup>-1</sup>) /  $Al_{CBD}$  (mg.kg<sup>-1</sup>)] \* 100

As expected, the  $\text{Fe}_{\text{AAO}}$  content was lower than the  $\text{Fe}_{\text{CBD}}$  content in all of the sampled soil horizons (Table 4.8), indicating that both crystalline and poorly crystalline Fe phases were present in the soils. The relationship between the different Al phases was more variable but according to Loeppert & Inskeep (1996) this is not unexpected seeing that the amount of Al extracted through these different reducing agents is soil dependent. Importantly, the determined  $\text{Fe}_{\text{CBD}}$  did not prove to show a significant difference between bleached and non-bleached topsoil horizons (Table 4.9, Figure 4.6a) which is in stark contrast to what was expected (Soil classification working group 1991). However, making use of the additional auger samples collected on the Highveld as part of this study and their corresponding XRF-determined Fe contents, bleached topsoil horizons proved to have a lower total Fe content compared to their non-bleached counterparts ( $p=0.02$ ). The probability of Fe loss therefore not being the cause of the bleached soil appearance is extremely unlikely, seeing that various authors including Torrent et al. (1983) and Fey (2010) report on the dominant pigmenting effect of Fe oxides in soils of comparable nature. In the study by Carstens (2015, Thesis submitted) a larger sample set of similar soils were used and a significant difference in  $\text{Fe}_{\text{CBD}}$  between bleached and non-bleached profiles was recorded. The abnormality in the generated statistics of this study is therefore proposed to rather be the result of the variability of the soils that were sampled in combination with the small size of the data set.

Noticeably, a significant difference was recorded in the subsoil  $\text{Fe}_{\text{CBD}}$  (Table 4.9, Figure 4.6b) between bleached and non-bleached profiles ( $p<0.01$ ), with a similar trend also being observed with subsoil  $\text{Fe}_{\text{AAO}}$  ( $p=0.07$ , Table 4.9). Overall more CBD and AAO extractable Fe was reported in the subsoils of non-bleached profiles. Per location, subsoil  $\text{Fe}_{\text{CBD}}$  was also significantly higher in the non-bleached Western Cape profiles whilst the Highveld subsoils further displayed a similar trend. This indicated that bleached profiles had an overall lower Fe content compared to their non-bleached counterparts. In the case of subsoil  $\text{Fe}_{\text{AAO}}$ , the non-bleached Western Cape profiles again exhibited a greater poorly crystalline Fe phase whilst no difference was detected between bleached and non-bleached Highveld profiles. However, it must be kept in mind that on the Highveld, soils were sampled from adjacent profile positions along a catenal transect where bleached topsoils were not observed on the redder Fe-rich soils. To be able draw conclusions about how the poorly-crystalline Fe contents changed, it is better to look at comparisons of the Fe crystallinity index.

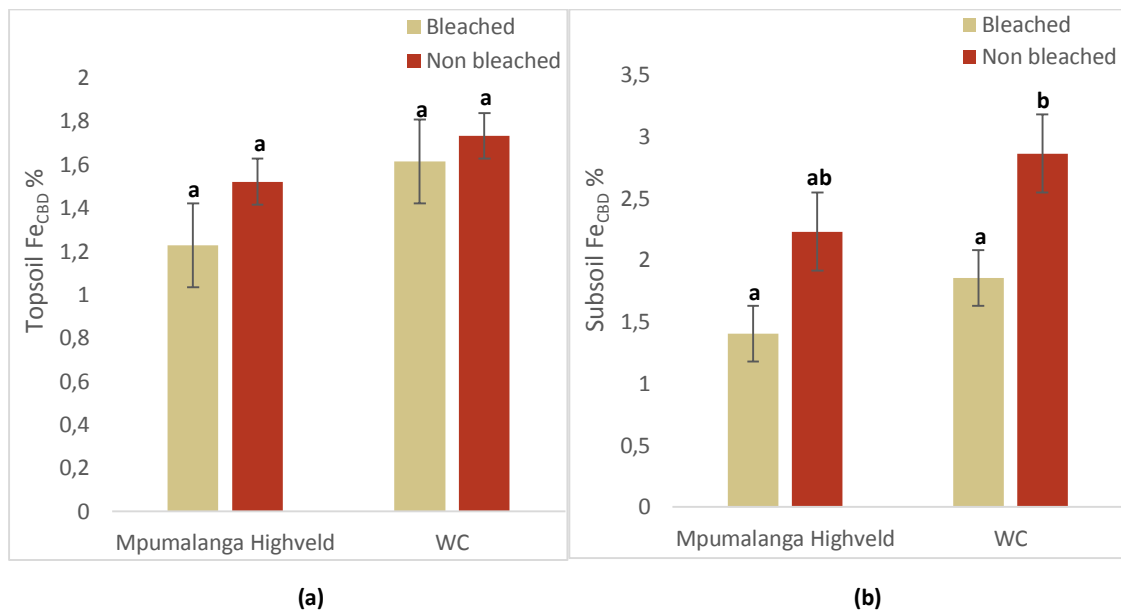
Both the recorded  $\text{Fe}_{\text{CBD}}$  and  $\text{Fe}_{\text{AAO}}$  contents tended to be higher in the Western Cape profiles compared to the Highveld, but proportionally similar amounts of crystalline and poorly-crystalline Fe oxides were present at the two locations as indicated by the similar top-and subsoil Fe CI values (Table 4.8). However, the CI tended to be higher in bleached compared to non-bleached topsoils with such a difference in the subsoil CI between bleached and non-bleached profiles not being as apparent (Table

4.9, Figures 4.7 and 4.8). This trend was more pronounced on the Highveld, where the CI of the topsoil Fe oxides was higher in bleached compared to non-bleached profiles. Noticeably, the subsoil Fe CI in this location also followed a similar trend although no such differences were observed in the Western Cape subsoils. A higher Fe CI indicates that similar amounts of crystalline and poorly-crystalline Fe is present within a horizon. The observed occurrence of relatively more poorly-crystalline Fe in the bleached profiles is indicative of more freshly-precipitated Fe oxides which may be attributed to a wetter soil moisture regime and alternating cycles of saturation and Fe reduction (Wahid & Kamalam 1993; Stumm & Morgan 1996; Thompson et al. 2011).

**Table 4.9.** The different extractable Fe phases of the sampled top- and subsoil horizons. Comparisons based on results generated by means of one-way and two-way ANOVAs.

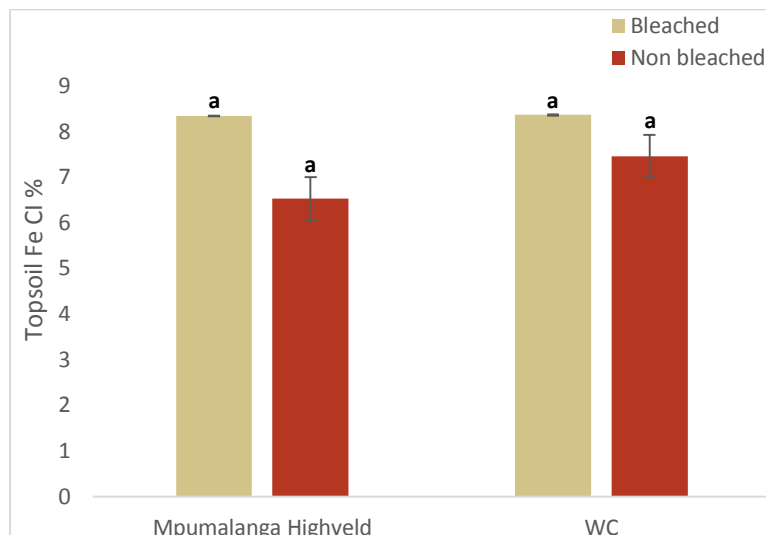
Grouping variables	F-value	p-value
<b>Topsoil Fe<sub>CBD</sub></b>		
WC vs MP Highveld	1.70	0.21
Bleached vs Non-bleached	0.81	0.38
WC: Bleached vs Non-bleached	0.15	0.70
MP Highveld: Bleached vs Non-bleached	0.15	0.39
<b>Topsoil Fe<sub>AAO</sub></b>		
WC vs MP Highveld	5.29	0.03*
Bleached vs Non-bleached	0.38	0.54
WC: Bleached vs Non-bleached	0.28	0.40
MP Highveld: Bleached vs Non-bleached	0.28	0.95
<b>Topsoil Fe CI %</b>		
WC vs MP Highveld	0.28	0.60
Bleached vs Non-bleached	2.23	0.15*
WC: Bleached vs Non-bleached	0.25	0.47
MP Highveld: Bleached vs Non-bleached	0.25	0.19*
<b>Subsoil Fe<sub>CBD</sub></b>		
WC vs MP Highveld	3.02	0.10*
Bleached vs Non-bleached	8.69	<0.01*
WC: Bleached vs Non-bleached	0.09	0.03*
MP Highveld: Bleached vs Non-bleached	0.09	0.09*
<b>Subsoil Fe<sub>AAO</sub></b>		
WC vs MP Highveld	6.87	0.02*
Bleached vs Non-bleached	3.67	0.07*
WC: Bleached vs Non-bleached	2.47	0.02*
MP Highveld: Bleached vs Non-bleached	2.47	0.82
<b>Subsoil Fe CI %</b>		
WC vs MP Highveld	0.30	0.59
Bleached vs Non-bleached	1.15	0.30
WC: Bleached vs Non-bleached	1.76	0.85
MP Highveld: Bleached vs Non-bleached	1.76	0.12*

(\* = significant differences & reported trends)

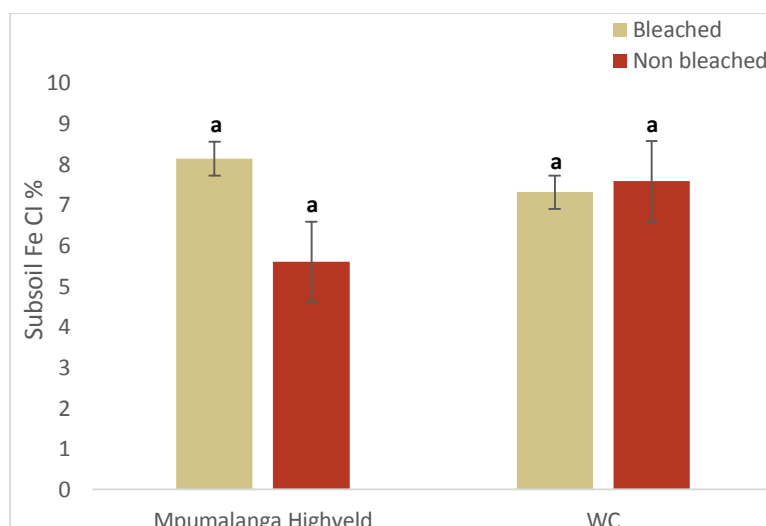


**Figure 4.6.** The top- (a) and subsoil (b) CBD extractable Fe contents of bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

Uncertainty surrounding the type and crystallinity of the Al oxides extracted by citrate-bicarbonate-dithionite and ammonium oxalate, together with the controversial influence of these minerals on clay stabilisation (Amézketa 1999) make clear interpretations about their role in bleaching and the overall dynamics of the sampled soils difficult. The results indicated that both top- and subsoil AAO Al did not differ between the locations or between the bleached and non-bleached profiles in each. However, top- and subsoil Al<sub>CBD</sub> tended to be higher in the soils from the Western Cape compared to Highveld ( $p=0.12$  &  $p=0.07$ ). The calculated Al ratio (Table 4.8) in contrary tended to be higher in the Highveld topsoil ( $p=0.06$ ) and subsoil ( $p=0.16$ ) horizons. Neither of these two parameters however had any connotation to bleaching. In conclusion, some variation in the Al fraction of the soils that were sampled were recorded but Al oxides had no detectable effect on the occurrence of bleaching in the topsoil horizons that were investigated.



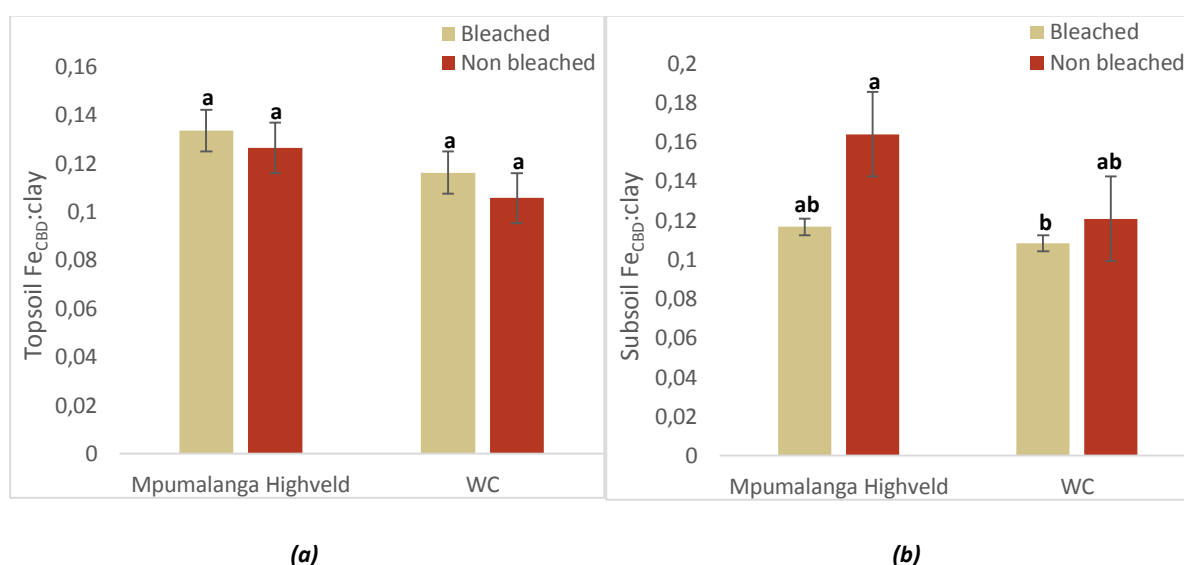
**Figure 4.7.** The calculated crystallinity index (CI) (%) of the soil Fe content for the sampled topsoil horizons of both bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.



**Figure 4.8.** The calculated crystallinity index (CI) (%) of the soil Fe content for the sampled subsoil horizons of both bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

Due to the known stabilising effect of Fe oxides on the soil colloidal fraction (Amézketa 1999; Duiker et al. 2003; Laker 2004), the Fe content of the sampled soils were normalised to the corresponding clay contents to investigate what relative quantity of Fe oxides resulted in what degree of clay stabilisation. This allowed comparison between soils with variable Fe and clay contents. A  $Fe_{CBD} : \text{clay}$  ratio was calculated for all the sampled horizons, which tended to be higher in the Highveld compared to the Western Cape top- and subsoil horizons ( $p=0.11$  &  $p=0.15$ , respectively) (Figures 4.9a and b). The subsoil  $Fe_{CBD} : \text{clay}$  ratio also proved to be slightly higher in the non-bleached Highveld profiles

compared to bleached variants ( $p=0.09$ ) (Figure 4.9b). It is expected that a higher  $Fe_{CBD}$ : clay ratio will imply that more Fe oxides are present to stabilise the clay fraction and limit clay dispersion. Therefore, the higher  $Fe_{CBD}$ : clay ratio registered on the Highveld for both top- and subsoil horizons is presumed to contribute to the stable clay phase recorded in these soils. In the Western Cape, however, results indicated that relatively less  $Fe_{CBD}$  per percentage of clay was present, which could enhance the dispersibility of the clay phase in these soils. Duiker et al. (2003) however warns against such literal interpretations and states that a variety of factors including the pH, crystal size, oxide genetic pathway, soil solution composition and the presence of certain organic molecules can also influence the stabilising effect that Fe oxides have in the soil. Nonetheless, the recorded ratios are in agreement with the measured clay dispersion parameters which indicate that some relationship does exist.



**Figure 4.9.** The normalised  $Fe_{CBD}$  to clay ratio of the sampled top- (a) and subsoil (b) horizons of bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

#### 4.3.2.4 Organic C and N

To characterise to some extent the organic matter content of the sampled soils was a definite priority due to organic matter's association with the Fe reduction process, its influence on clay stabilisation and of course its known soil pigmentation effect. Organic C drives soil redox chemistry and will essentially fuel Fe reduction under anaerobic conditions (Wheeler et al. 1999). In addition, the C:N ratio of a soil is also a commonly used to indicate what microbial mediated processes will occur within the soil (Hazelton & Murphy 2007). From the obtained results, the organic C contents of the sampled horizons were low but in agreement to what is expected for mineral soils under South African conditions (Fey 2010), with the topsoil C content also being higher than subsoil values in all of the



sampled profiles (Table 4.10). The C: N ratios proved to be more variable and did not follow such a trend.

Significance testing indicated that topsoil C content was substantially higher in the Western Cape compared to the Highveld (Table 4.11, Figure 4.10). The topsoil C:N ratio however, showed no difference between the locations but rather tended to be higher in bleached compared to non-bleached horizons (Table 4.11, Figure 4.11a). This observed trend was the result of the significantly higher C:N ratios that were determined in the bleached Western Cape topsoils compared to the non-bleached variants. Subsoil C content was, as expected, more variable and proved to not differ between the locations or between the bleached and non-bleached profiles (Table 4.11). In the Western Cape, subsoils from bleached profiles tended to have a greater organic C content ( $p=0.15$ ). The subsoil C: N ratio proved to be significantly higher in the Highveld and also tended to be higher in bleached compared to non-bleached profiles (Table 4.11, Figure 4.11b).

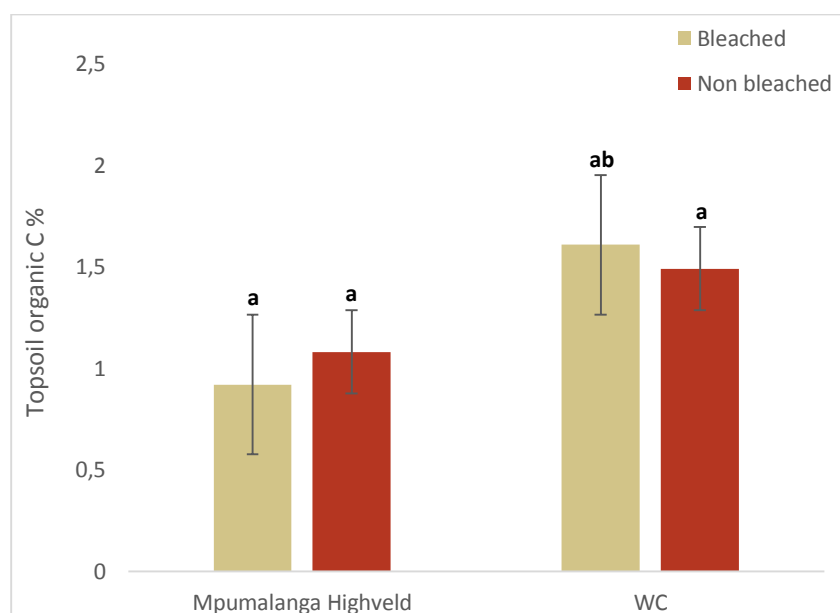
**Table 4.10.** Top- and subsoil carbon content (%) and the calculated C: N ratio. The value range, mean and standard deviation (SD) for both the top- and subsoil horizons of each location are given.

	Western Cape				Mpumalanga Highveld			
	Bleached		Non-bleached		Bleached		Non-bleached	
	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD
<i>Topsoil C (%)</i>	0.97-2.36	<b>1.61</b> $\pm$ 0.48	0.87-2.85	<b>1.49</b> $\pm$ 0.70	0.74-1.11	<b>0.92</b> $\pm$ 0.16	0.87-1.55	<b>1.08</b> $\pm$ 0.27
<i>Topsoil C:N</i>	11.06-40.64	<b>23.35</b> $\pm$ 10.26	9.80-24.72	<b>14.06</b> $\pm$ 5.16	14.75-24.64	<b>18.08</b> $\pm$ 3.85	13.71-24.41	<b>18.35</b> $\pm$ 3.37
<i>Subsoil C (%)</i>	0.64-1.34	<b>0.92</b> $\pm$ 0.27	0.54-1.22	<b>0.75</b> $\pm$ 0.25	0.70-0.87	<b>0.76</b> $\pm$ 0.07	0.51-0.97	<b>0.77</b> $\pm$ 0.16
<i>Subsoil C:N</i>	0.0-47.8	<b>20.72</b> $\pm$ 14.11	8.77-18.75	<b>14.95</b> $\pm$ 3.78	19.82-36.71	<b>29.88</b> $\pm$ 6.86	12.76-47.16	<b>22.38</b> $\pm$ 11.30

**Table 4.11.** Comparisons between the organic carbon (%) and C: N ratios of the sampled top- and subsoil horizons by means of one-way and two-way ANOVAs.

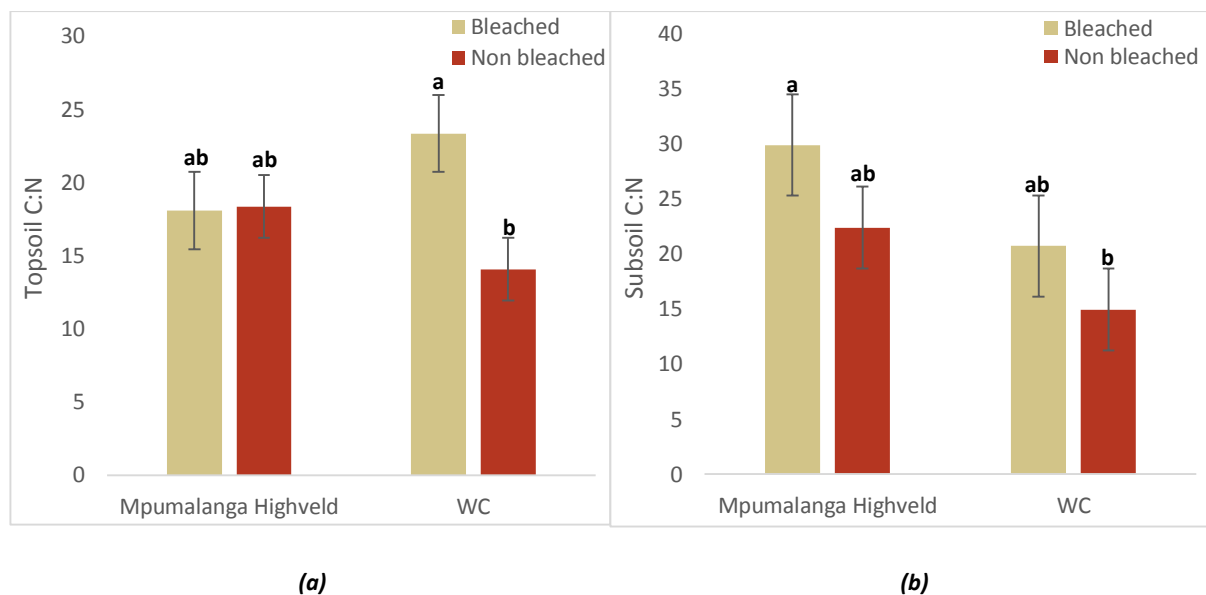
Grouping variables	F-value	p-value
<b>Topsoil C %</b>		
WC vs MP Highveld	8.64	<0.01*
Bleached vs Non-bleached	0.01	0.91
WC: Bleached vs Non-bleached	0.55	0.65
MP Highveld: Bleached vs Non-bleached	0.55	0.57
<b>Topsoil C:N</b>		
WC vs MP Highveld	0.04	0.85
Bleached vs Non-bleached	3.09	0.09*
WC: Bleached vs Non-bleached	3.48	0.01
MP Highveld: Bleached vs Non-bleached	3.48	0.94
<b>Subsoil C %</b>		
WC vs MP Highveld	0.61	0.44
Bleached vs Non-bleached	0.91	0.35
WC: Bleached vs Non-bleached	1.14	0.15*
MP Highveld: Bleached vs Non-bleached	1.14	0.94
<b>Subsoil C:N</b>		
WC vs MP Highveld	4.31	0.05*
Bleached vs Non-bleached	2.76	0.11*
WC: Bleached vs Non-bleached	0.05	0.30
MP Highveld: Bleached vs Non-bleached	0.05	0.22

(\* = significant differences &amp; reported trends)

**Figure 4.10.** The topsoil organic C content of both the sampled bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

The lower topsoil C content registered in the Highveld compared to the Western Cape profiles is again likely a result of cultivation practices. Conventional tillage practices enhances organic matter decomposition by amongst others, destroying the physical protection provided by soil aggregates and

therefore results in lower organic C contents (Balesdent et al. 2000). In the undisturbed Western Cape profiles, normal organic matter accumulation and decomposition processes will not have been altered or enhanced in any way. The soil mixing action of conventional tillage practices can also result in the translocation of organic material from topsoil- to subsoil horizons, which can explain the higher subsoil C:N ratio in the Highveld profiles. What did prove interesting was the higher topsoil C:N ratio in bleached profiles in the Western Cape. The data generated in this study does not enable clear conclusions about the significance of this feature and to explain its influence more research is therefore required.



**Figure 4.11.** The top- (a) and subsoil (b) C: N ratio of both the sampled bleached and non-bleached profiles in the Western Cape and Mpumalanga Highveld. Standard error bars and significance letters are indicated.

#### 4.3.3 Mechanisms of topsoil bleaching

The comprehensive nature of the data collected on the sampled soil profiles of the Western Cape and Mpumalanga Highveld meant that various different dimensions surrounding the bleaching of topsoil horizons under weakly structured subsoil conditions have to be discussed in order to better understand what is pedogenetically implied by this soil phenomenon. Soil-landscape relationships together with particular components of the presented chemical and physical profile characteristics have to be discussed in combination to be able to explain the mechanism by which bleached topsoil horizons originate in the weakly structured soil profiles of the Western Cape and Mpumalanga Province. To condense the generated dataset, PCA biplots were generated (Appendix 4.8) but unfortunately provided no conclusive information regarding the bleaching of topsoils in either of the two locations. These biplots were consequently not included as part of the current discussion. The

variability with which soil characteristics were expressed in the sampled profiles as well as the different influences related to these expressions were deemed to be responsible for this result.

#### 4.3.3.1. *Evidence for Fe reduction: Soil-landscape relationships*

Milne's work in East Africa is arguably the first comprehensive record of the relationships that exists between soil characteristics and landscape features (Milne 1935) and today, the influence of landscape dynamics on soil pedogenesis is widely recognised and has been well-studied (Huggett 1975; Gessler et al. 1995). Within the current pedological sphere, very few studies can afford to overlook the landscape's contribution toward soil genetic processes. Although the initial layout of this study did not include investigating soil-landscape relationships *per se*, field observations necessitated the inclusion of this facet into the overall framework and also resulted in a change in the soil sampling approach, particularly on the Mpumalanga Highveld. Important observations regarding the occurrence of bleached topsoils, the type of well-drained subsoil they overlie and the landscape relationships associated with this feature were made in both the locations where profiles were sampled. Firstly and most importantly, bleaching on the Mpumalanga Highveld was observed to be landscape related with bleached orthic A horizons only occurring on yellow-brown apedal B subsoil horizons in either midslope or footslope positions along the red-yellow-grey plinthic catenas commonly found in these parts of South Africa. In the Western Cape however, the bleached profiles did not always seem to follow a landscape pattern and had both red and yellow weakly structured B horizons. These observable differences between the two locations meant that sampling on the Mpumalanga Highveld was conducted along catenal transects whereas the sampled Western Cape profiles were simply selected based on weak structured subsoil condition and the presence or absence of bleaching in the topsoil.

The discrepancy between bleached and non-bleached soils based on perceived and measured colours resulted in different profile groupings and slight differences in the landscape characteristics of each group between the two locations (Tables 4.12 and 4.13). Based on the slope type and slope gradient little evidence exists to distinguish the bleaching phenomenon from non-bleached variants. Slope gradients in the Western Cape were greater for both bleached and non-bleached profiles compared to that which was recorded on the Highveld. The significance of the landscape information provided in Tables 4.12 and 4.13 is more related to the differences in the distribution of bleached and non-bleached profiles along the different terrain units in the Western Cape and Mpumalanga Highveld. Although only minor differences can be observed between the relative frequencies of these groupings, bleached topsoils occurred exclusively in upper midslope positions in the Western Cape. This is in agreement with the proposed geomorphic history of these soils (Lambrechts 1983). These landscape positions are usually intermediately well-drained and therefore red- and yellow soil colours are

present as a result of Fe oxide coatings on the soil mineral particles (Fey 2010; van Tol et al. 2011). Interestingly, non-bleached profiles also predominantly occurred in these positions or even lower down the slope in theoretically wetter topographical units. From the information provided in Table 4.12 and 4.13, it is suggested that i) landscape position did not have such an observable influence on the occurrence of bleaching in the Western Cape, and ii) the corresponding wetness associated with each terrain unit did not seem to be the primary cause for bleaching in this province.

On the Highveld the bleaching phenomenon was recorded primarily on lower midslopes within the transition zone towards the footslope positions. Non-bleached profiles were found along the entire spectrum of topographical positions also including the lower lying areas but in this regard a couple of important factors need to be considered when interpreting the presented data in Table 4.12 and 4.13. Firstly, the spectrum of terrain units is predominantly a consequence of sampling along a catenal transect. Secondly, this study made no distinction between borderline bleached or non-bleached colour conditions mainly for statistical purposes and therefore some of the non-bleached profiles recorded in the lower lying areas exhibited very prominent bleaching tendencies similar to that which was noted by Van der Waals (2013) but which also did not qualify based on the specified colour criteria (Soil classification working group 1991). The spectrophotometer however, classified these horizons as bleached and therefore more bleached profiles were recorded based on instrument-measured colours, as seen in Table 4.13. Lastly, in order to better interpret the landscape information provided in Tables 4.12 and 4.13 one must be made aware of the size of the area in question i.e. where bleached topsoils overlay well-drained yellow-brown apedal B horizons along these catenas. This area will undeniably range in size from one catena to the next but based on the catenas that were sampled in this study, this specific soil sequence occurred within a band never exceeding 10 to 12 meters in width. This of course is on a much smaller scale than what would be used to distinguish between landscape terrain units, implying that in some instances where the transition in topsoil colour from non-bleached to bleached occurred within a small distance between sampled points, both bleached and non-bleached profiles were registered on the same terrain unit, distorting the evident landscape related expression of bleaching within this region. Therefore, to better illustrate the proposed relationship that exists between landscape position and bleached topsoils on the Mpumalanga Highveld, soil cross sections were generated of the four catenas that were sampled (Figures 4.12-4.19).

**Table 4.12.** Landscape and terrain characteristics of the individual profiles recorded during field sampling based on perceived soil colours determined by means of visual comparison with the Munsell soil colour chart. The relative frequencies of the terrain units and slope types are given as well as the range and mean slope gradients (%) of the sampled profiles.

	Western Cape		Mpumalanga Highveld	
	Bleached	Non-bleached	Bleached	Non-bleached
<b>Terrain unit<sup>1</sup></b>				
<i>1</i>	-	-	-	1
<i>3U</i>	6	5	1	4
<i>3L</i>		2	2	2
<i>4</i>	-	1	-	2
<b>Slope type<sup>2</sup></b>				
<i>Convex</i>	3	2	-	1
<i>Concave</i>	-	3	2	3
<i>Straight</i>	-	2	1	4
<i>Straight-Convex</i>	2	1	-	-
<i>Straight-Concave</i>	-	-	-	1
<b>Slope % range</b>	2-25	3-9	0.5-4	0.5-4
<b>Slope % mean</b>	8.0 ± 8.6	6.6 ± 2.1	2	1.6 ± 1.5

<sup>1</sup> 1=crest, 3U=upper midslope, 3L=lower midslope, 4=footslope; <sup>2</sup> Profile Hh 4 omitted due to human disturbance

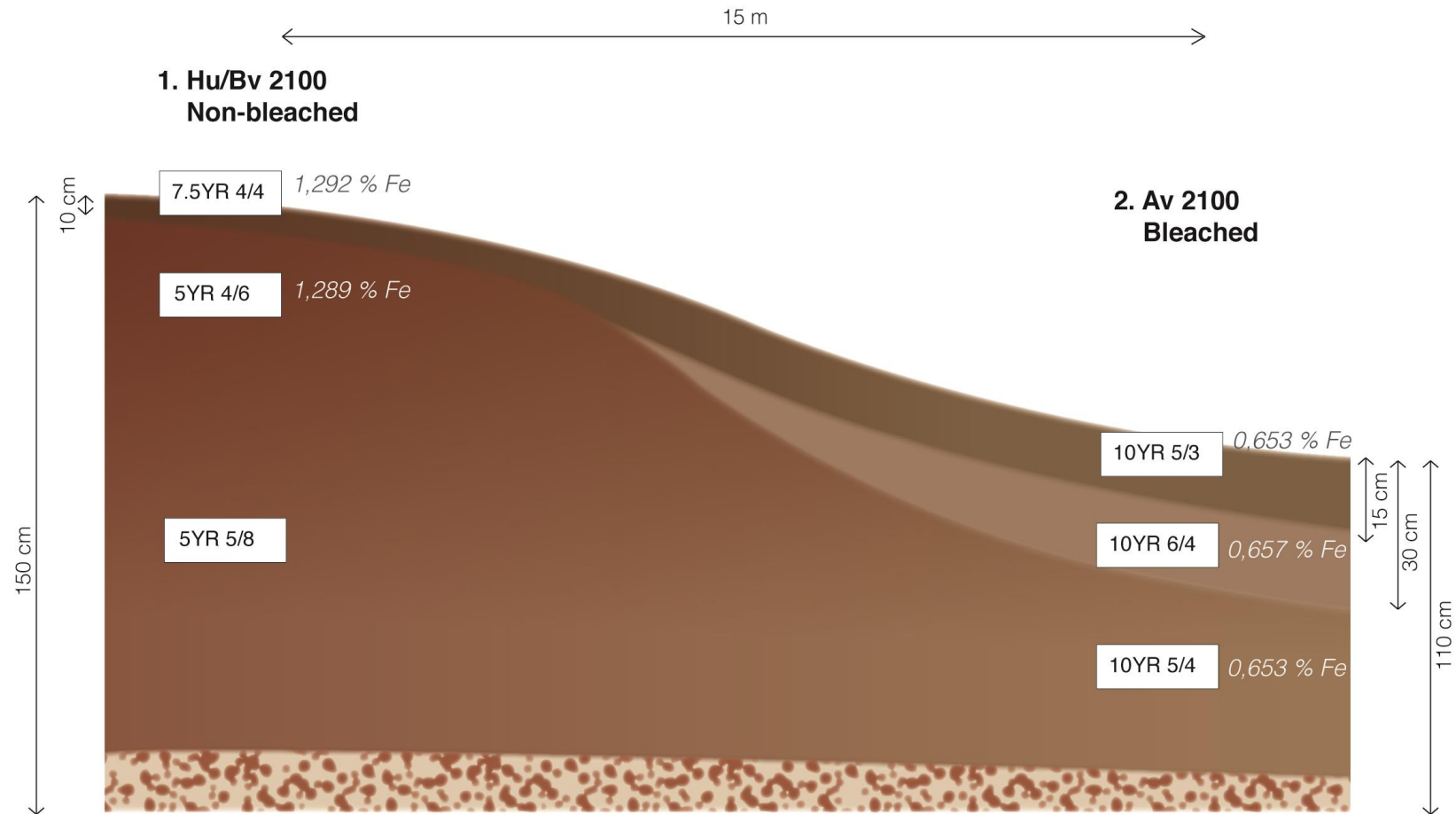
**Table 4.13.** Landscape and terrain characterisation of the sampled profiles following colour measurement with the spectrophotometer. The relative frequencies of the terrain units and slope types are given as well as the range and mean slope gradients (%) of the sampled profiles.

	Western Cape		Mpumalanga Highveld	
	Bleached	Non-bleached	Bleached	Non-bleached
<b>Terrain unit<sup>1</sup></b>				
<i>1</i>	-	-	-	1
<i>3U</i>	7	4	1	4
<i>3L</i>		2	3	1
<i>4</i>	-	1	1	1
<b>Slope type<sup>2</sup></b>				
<i>Convex</i>	2	3	-	1
<i>Concave</i>	1	2	3	2
<i>Straight</i>	1	1	1	4
<i>Straight-Convex</i>	2	1	-	-
<i>Straight-Concave</i>	-	-	1	-
<b>Slope % range</b>	2-25	3-8	0.5-4	0.5-4
<b>Slope % mean</b>	8.4 ± 7.8	6 ± 1.9	2.5 ± 2.1	2.2 ± 1.6

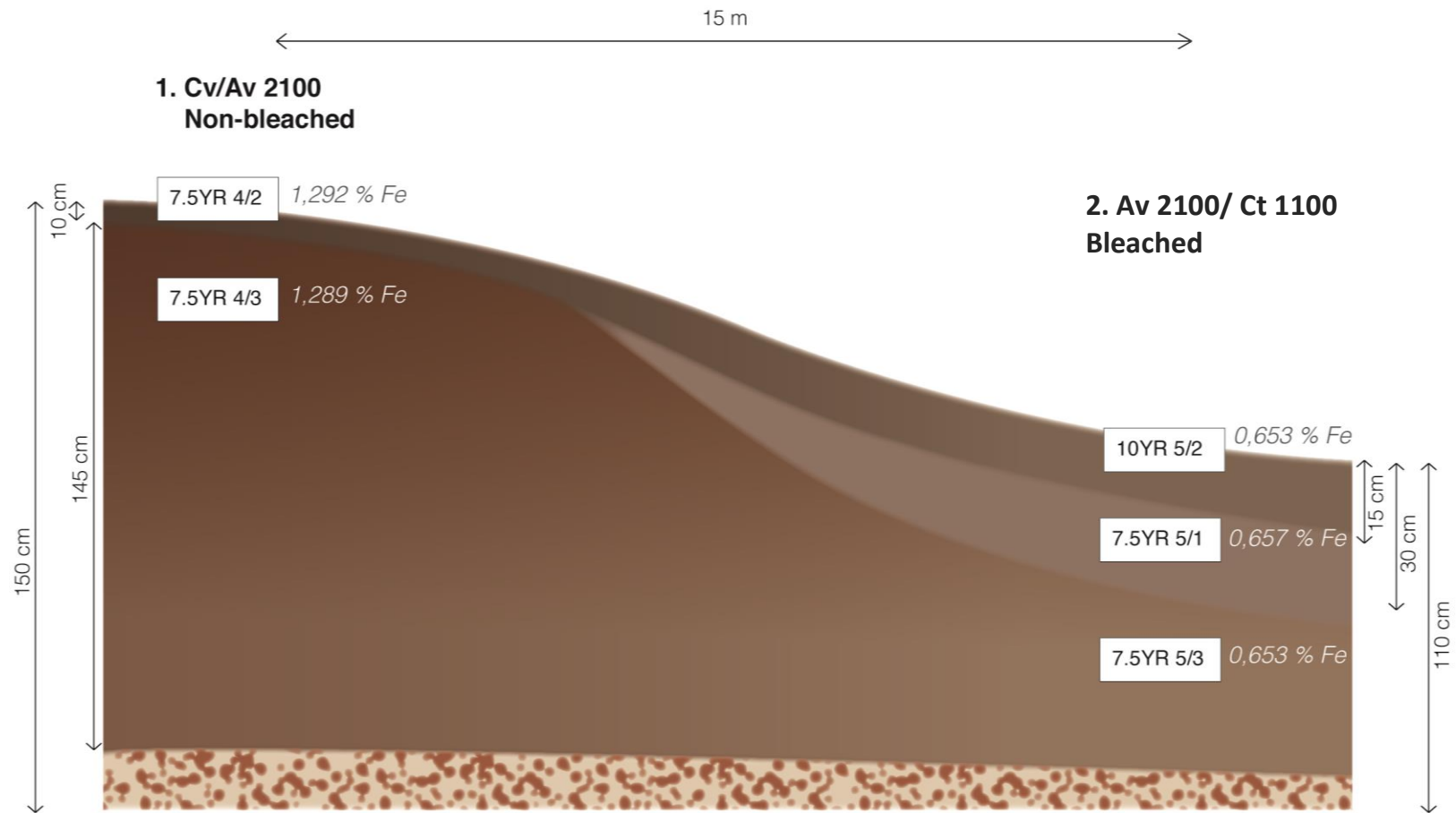
<sup>1</sup> 1=crest, 3U=upper midslope, 3L=lower midslope, 4=footslope; <sup>2</sup> Profile Hh 4 omitted due to human disturbance

The term catena describes a predictable sequence of soils related to specific topographical positions within the landscape (Milne 1935). In South Africa, an extensive part of the country's interior is occupied by a catena which, in its perfect form is represented by red soils on well-drained crests grading through yellow soils on midslope positions towards gleyed colours (predominantly grey) in the poorly-drained footslopes and valley bottoms (Soil and Irrigation Research Institute 1987; Fey 2010). The presence of plinthic horizons at varying depths throughout this catena has given rise to its name the red-yellow-grey plinthic catena or more commonly the Highveld plinthic catena. As can be seen from Figures 4.12 to 4.19 the soils that were sampled followed this typical red-yellow-grey catenal sequence. Slight differences in the expressed soil colours and horizon sequences were recorded between the individual catenas and clear differences were also observed between profile classification and characterisation based on perceived and measured soil colours. Nonetheless, collective trends were observed among the sampled catenas with specific reference to bleaching and the determined soil colour variations and more importantly, the existence of bleached topsoils overlying well-drained yellow-brown apedal B subsoil horizons were verified (van der Waals 2013).

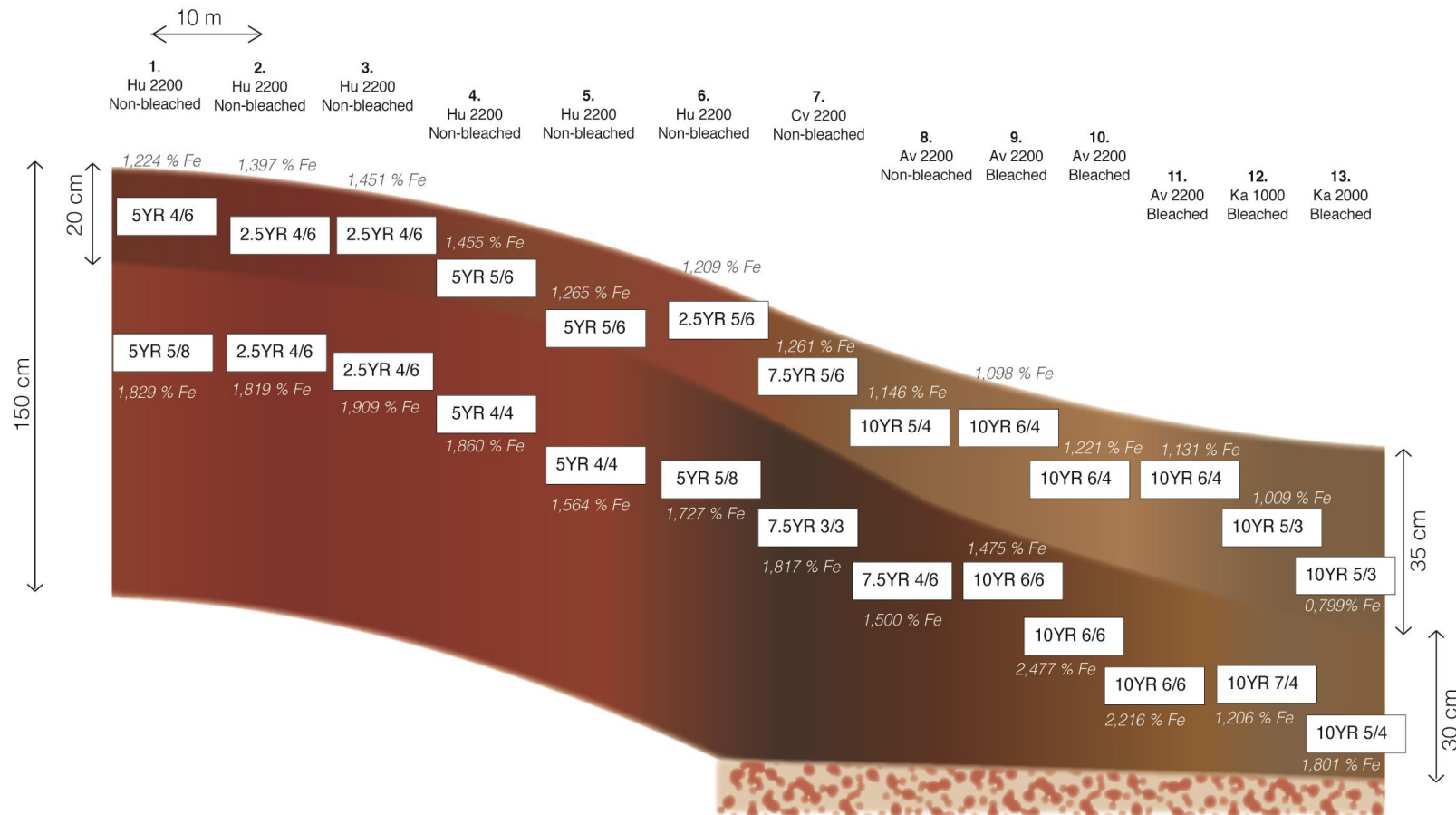




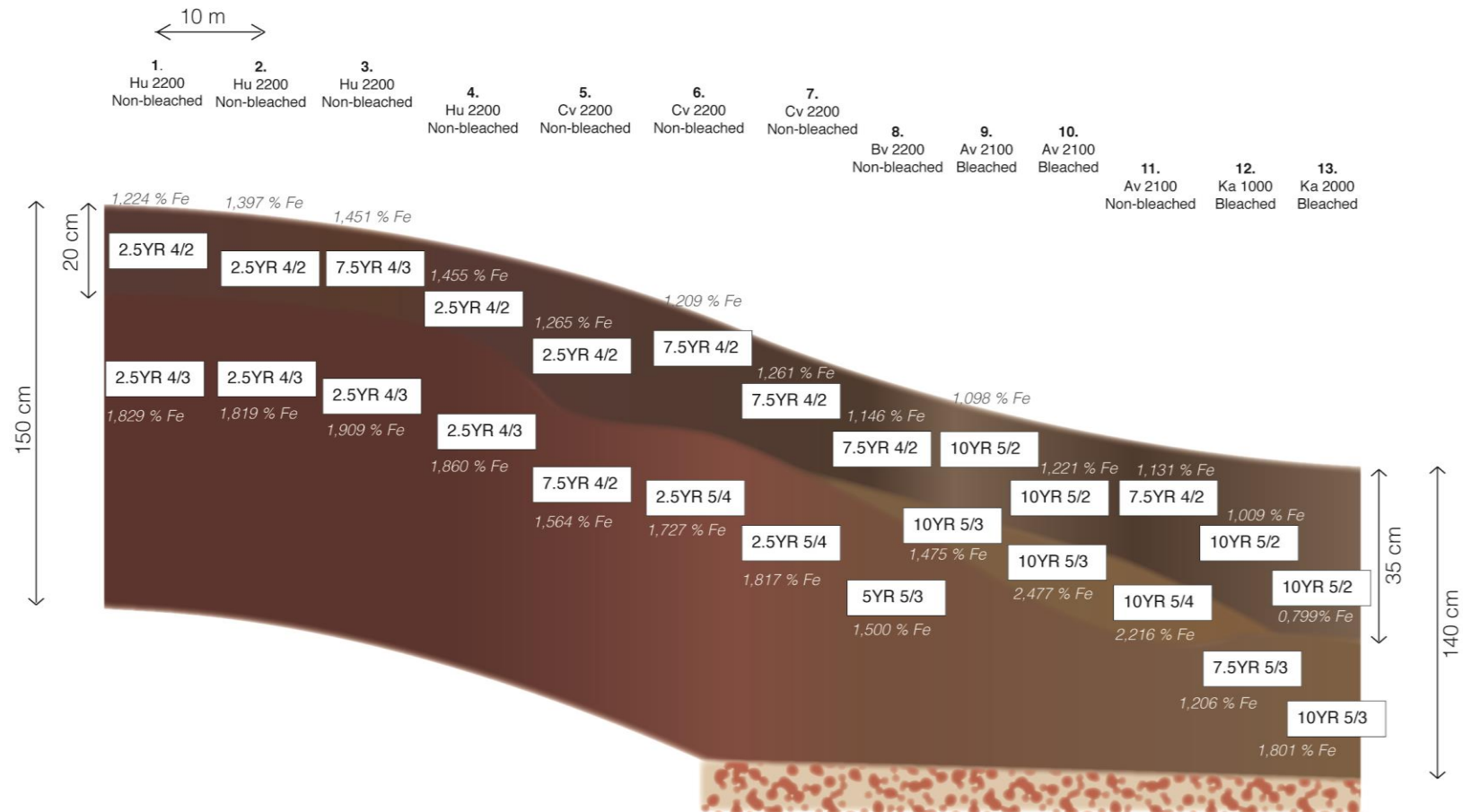
**Figure 4.12.** Catena 1 – perceived soil colour. Cross section of catena 1 with soil classification and characterisation based on perceived colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.



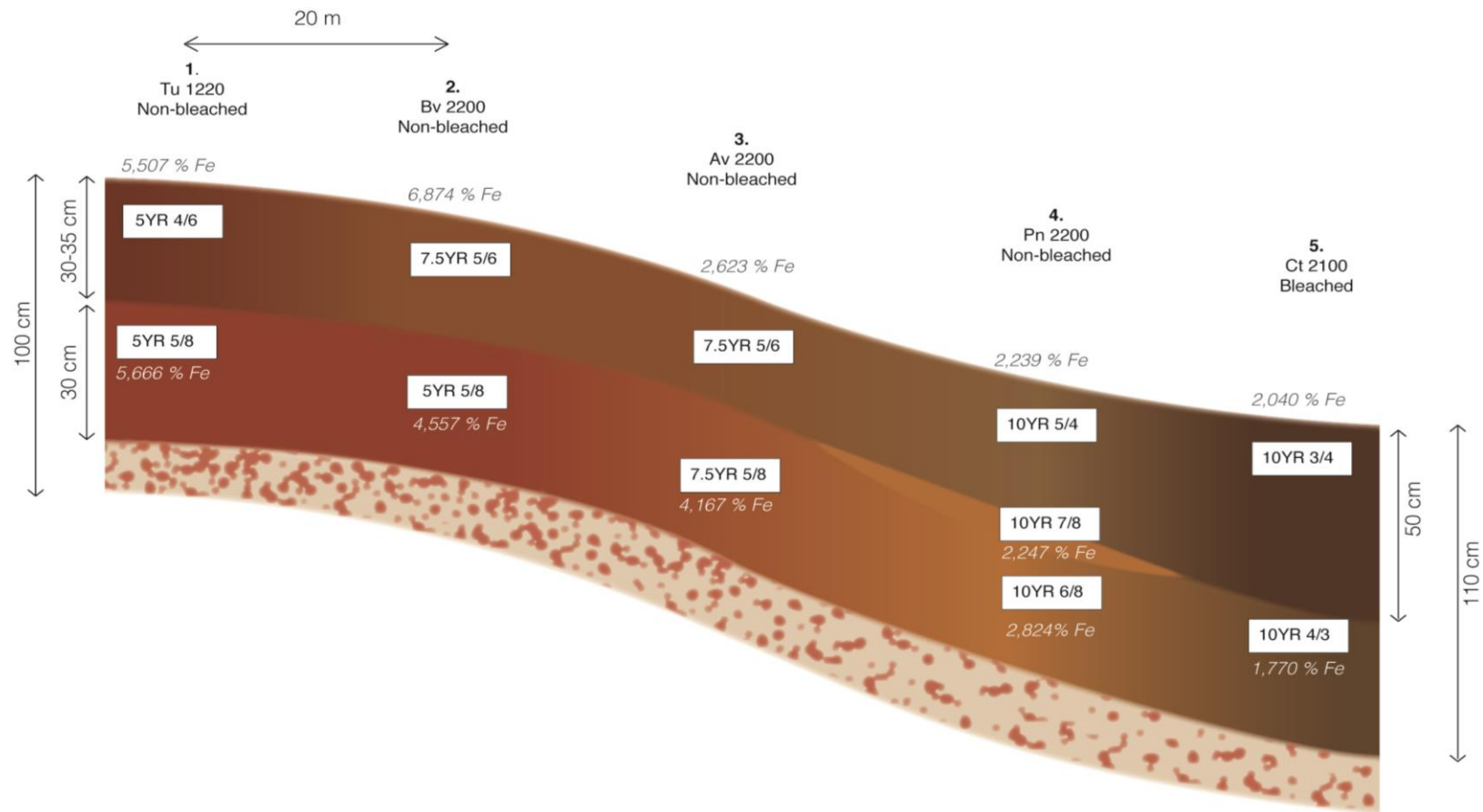
**Figure 4.13.** Catena 1 – measured soil colour. Cross section of catena 1 with soil classification and characterisation based on instrument-measured colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.



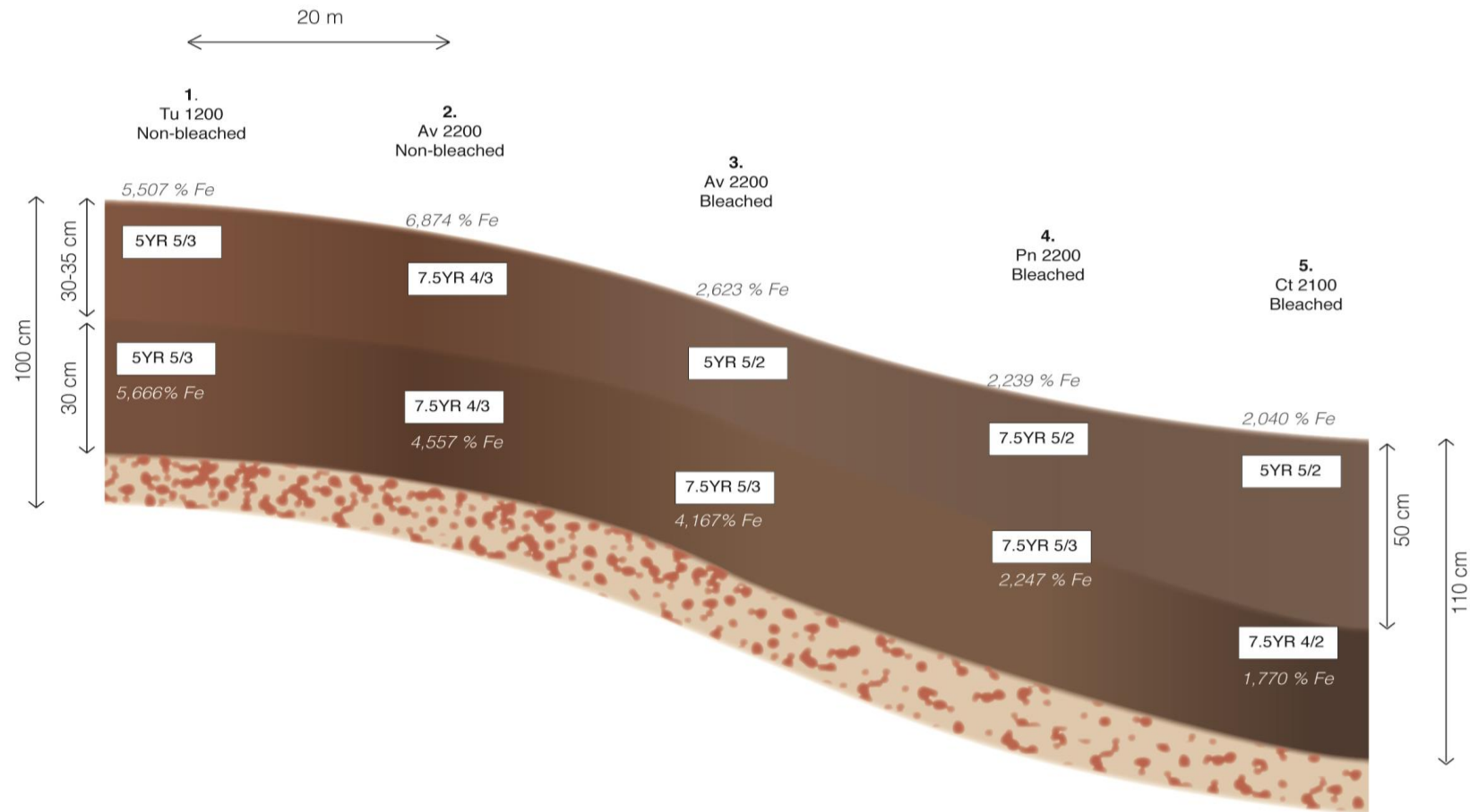
**Figure 4.14.** Catena 2 – perceived soil colour. Cross section of catena 2 with soil classification and characterisation based on perceived colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.



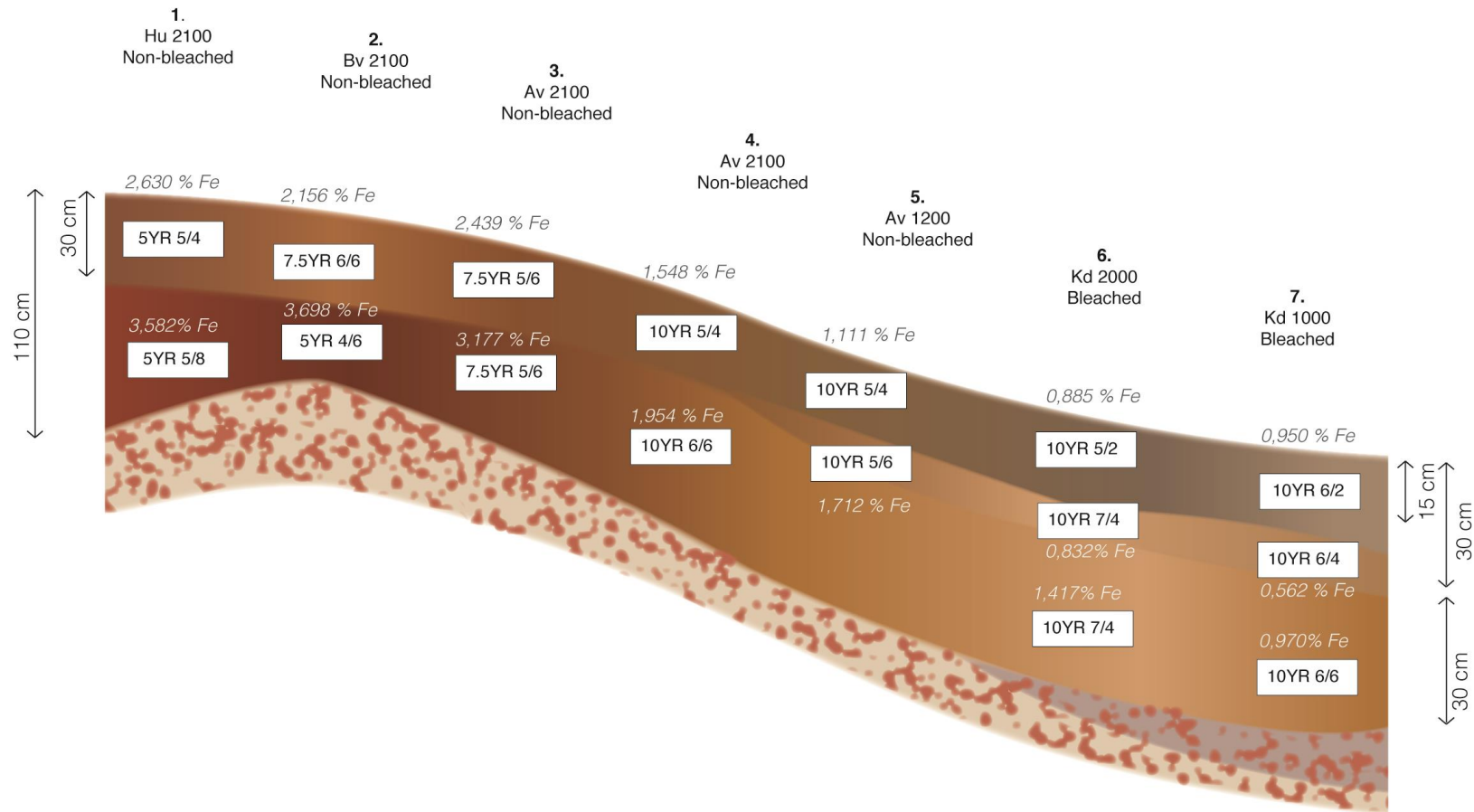
**Figure 4.15.** Catena 2 – measured soil colour. Cross section of catena 2 with soil classification and characterisation based on instrument-measured colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.



**Figure 4.16.** Catena 3 – perceived soil colour. Cross section of catena 3 with soil classification and characterisation based on perceived colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.

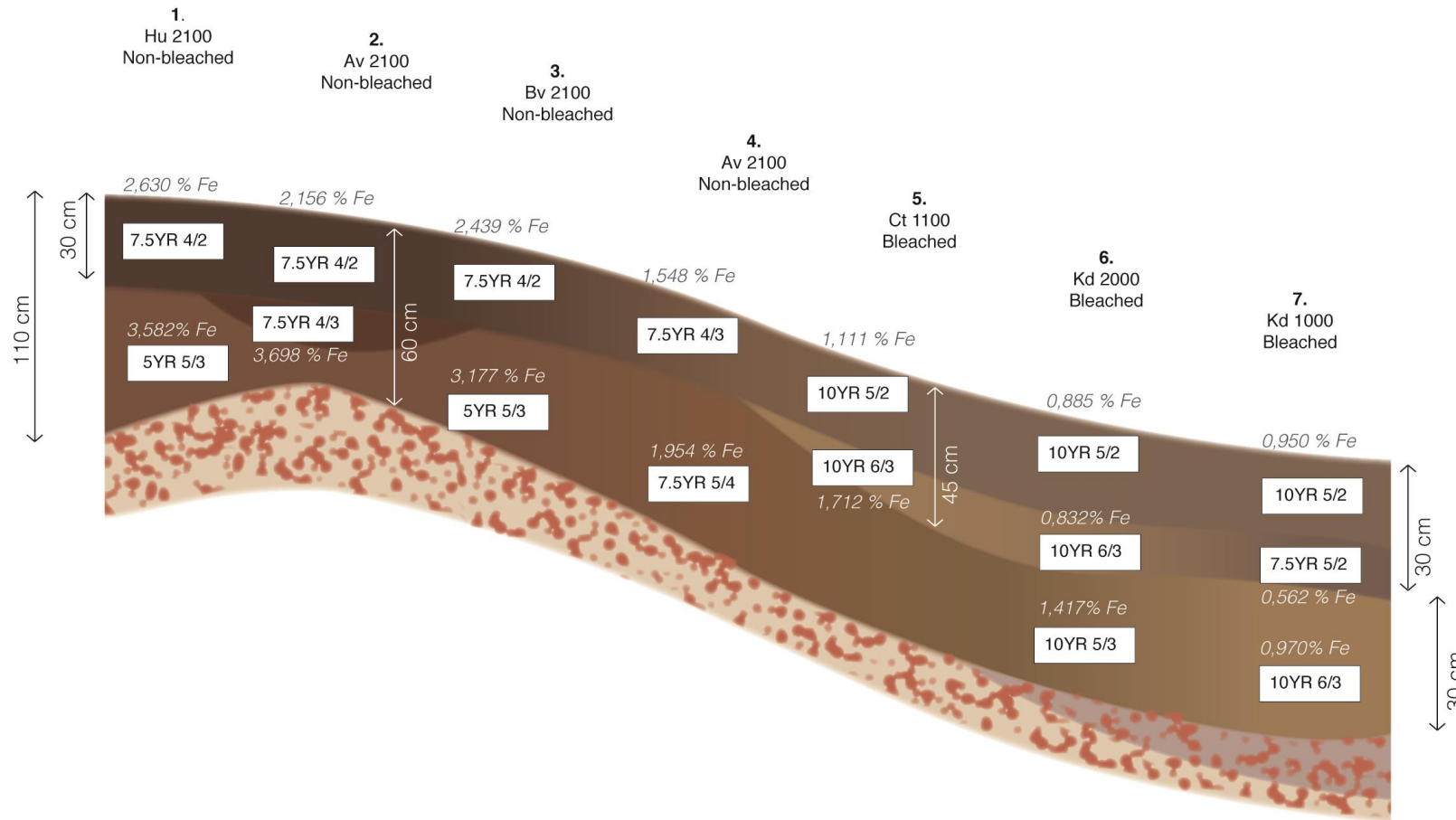


**Figure 4.17.** Catena 3 – measured soil colour. Cross section of catena 3 with soil classification and characterisation based on instrument-measured colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.



**Figure 4.18.** Catena 4 – perceived soil colour. Cross section of catena 4 with soil classification and characterisation based on perceived colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.





**Figure 4.19.** Catena 4 – measured soil colour. Cross section of catena 4 with soil classification and characterisation based on instrument-measured colours. The XRF determined Fe content of the different positions along the catena are also indicated. Soils were classified according to the South African classification system. **Note:** the slope gradient of the catena is exaggerated.

*Catena 1* (Figures 4.12 and 4.13) was the only catena that consisted of undisturbed soils that were not previously under cultivation. The parent material was suggested to be Fe-rich sandstone (van der Waals, 2014 pers. comm.) Only two profiles 15 m apart from one another were sampled, each on opposing sides of the transition zone between a non-bleached and bleached topsoil. Subsoil colour followed a gradual transition from a reddish-brown (Position 1) to a more yellow-brown matrix (Position 2) and a change in the depth at which plinthite occurred was also recorded. Based on the perceived colours (Figures 4.1) the soil form recorded at respectively Position 1 was a Hutton/Bainsvlei transition (orthic A – red apedal B – plinthite at  $\pm 150$  cm depth) and at Position 2 an Avalon (orthic A – yellow-brown apedal B – soft plinthic B) (Soil classification working group 1991). According to the instrument-measured soil colour, the more reddish-brown colour of the B horizon observed at Position 1 did not allow it to qualify as a diagnostic red apedal B and accordingly the classification of this profile was changed to an Avalon (Figure 4.13). Notably, the instrument measured a colour of 7.5YR 5/3 in the B horizon at position 2 which is not included in any of the diagnostic colour ranges in the soil classification system of South Africa (Soil classification working group 1991). The documented family criteria indicates a mesotrophic (intermediately leached) and non-luvic (limited textural contrast between A and B) B horizon was present in both profiles. The A horizon observably thickened from position 1 to position 2 (10 to 30 cm) which alluded to the potential presence of an E horizon at a depth of  $\pm 15$  cm. The bottom of this thickened A horizon however appeared to be more like an A/B transition zone comprising of a mixture of bleached and yellow-brown soil material. A border-line bleached colour was visually recorded along the bottom parts of this thickened horizon and this, together with the fact that the horizon did not exceed 350 mm in depth, provided the justification behind recognising only a bleached orthic A horizon in this profile. According to the Soil classification working group (1991, p. 19) “As these ‘grey’ A horizons become thicker, however, a point, difficult to identify especially in sands, is passed after which an E horizon, which cannot easily be distinguished from the ‘grey’ A horizon, is definitely present. When such difficulty exists, an E horizon should be regarded as being present when the material beneath 350 mm depth qualifies as a diagnostic E horizon”. Upon re-measuring the colours with the spectrophotometer, the instrument registered a much more definitive bleached colour within this transition zone (Figure 4.13) but due to the above-mentioned depth limitations and the fact that visual observations tended towards an A/B transition zone rather than an E horizon, profile classification was again inclined to exclude a diagnostic E horizon from the recorded horizon sequence. Nonetheless, the difference in the measured colours between the upper and lower parts of this thickened A horizon implies that an E horizon cannot be completely excluded and therefore the profile was classified as an Avalon/Constantia (orthic A - E - yellow-brown apedal B) soil form. The XRF determined Fe content in the top- and subsoil horizons at position 1 was

comparable but showed a substantial decrease in both horizons down the slope towards position 2 (Figures 4.12 and 4.13). The field-estimated texture at both these positions were similar for the top- and subsoil horizons.

*Catena 2* (Figures 4.14 and 4.15) was believed to be sandstone-derived and occurred within a field actively used for maize cultivation. The soil colour sequence again followed the typical red-yellow-grey pattern although the detail at which sampling was done along this catena (auger 13 holes, 10 m apart, starting in red and ending in grey) meant that even the slightest variation in soil colour was noticed. Particularly along the midslope at Position 7 the subsoil was perceived to be unnaturally dark, in contrast to the instrument-measured lighter red colour. Although the colour variation within this landscape positions seemed out of place, one must not neglect to take into account the influence of micro topography, where a small depression in the landscape (e.g. a slight concave or convex slope type on a midslope) can result in different drainage features and water flow characteristics resulting in unexpected soil colour expressions (Peterschmitt et al. 1996). Evidence to support such a cause for the colour discrepancy recorded at Position 7 can be observed in the XRF determined Fe content. As can be seen in Figures 4.14 and 4.15, subsoil Fe content increases slightly in these positions alluding to either an accumulation of Fe oxides or a hindered removal thereof. A thickening of the A horizon was also observed as with *Catena 1* but where this A horizon was perceived and measured to be bleached, it did not exceed a thickness of 350 mm and no clear E horizon was visible. Again, the bottom of this thickened A horizon looked much more like a transition zone between the A and B horizon (i.e. a mixture of yellow-brown and bleached colours) than an E horizon. XRF determined Fe content followed a similar pattern as *Catena 1* with the Fe content predominantly decreasing from the top to the bottom of the catena. The higher Fe content at the footslope position (Position 13) is most probably due to laterally transported ferrous Fe that was deposited and re-oxidised (Peterschmitt et al. 1996; Fey 2010). Field-estimated texture classified the soils at most positions as being luvisc and also recorded a clay increase down the slope in both the top- and subsoil horizons.

*Catena 3* (Figures 4.16 and 4.17) again consisted of soils used for maize cultivation. What made this catena unique however, was the presence of ferruginised shale, hard Fe concretions and quartz gravel that was recorded throughout the profile giving the impression that the soil material was transported (Appendix 2.1). The presence of numerous small ferruginised rock fragments is proposed to be the cause for the higher XRF Fe contents recorded for this catena. Five holes were augered 20 m apart from one another along the catena and sampling was ceased before a subsoil G horizon was reached at the bottom of the catena. The thickening of the A horizon, as observed in the previous two catenas, was much more exaggerated and although the bottom of this thickened A horizon was morphologically very similar to that recorded in the previous two catenas (A/B transition zone rather

than an E horizon), the prominent bleached colour as well as the depth of bleaching (>350 mm) meant that an E horizon was recognised. The classification outcome was a luvic Constantia soil form with no podzolic character beneath the B horizon (Soil classification working group 1991).

Probably the most significant aspects of this catena was i) the way in which the colour sequences in the top- and subsoil changed along the catena, and ii) the marked differences in where bleaching was detected by means of visual colour determination and the spectrophotometer measurements. As can be seen from Figures 4.15 and 4.16 the eye was unable to detect the bleaching condition higher up on the catena. These soil profiles were classified as non-bleached Avalon and Pinedene (orthic A – yellow-brown apedal B – unspecified material with signs of wetness) soil forms (Soil classification working group 1991). Upon the re-measurement of these soil colours with the instrument, the topsoil of the two profiles at positions 3 and 4 qualified as bleached, which meant that again bleached A horizons overlying well-drained yellow subsoils were present. Thus, both under measured and perceived soil colours, there seems to be an unsynchronised change in soil colour from red to yellow to grey between the top- and subsoil. This results in the catenal subsoil colour change (red-yellow-grey) lagging behind topsoil colour change as one moves down the slope. The result is an overlap in bleached topsoils and yellow-brown subsoil horizons. The XRF determined Fe contents again decreased with the change in colour from red to yellow to grey in both the top-and subsoil, with the field-estimated clay content increasing in the same direction.

Sampling along *Catena 4* (Figures 4.18 and 4.19) comprised of 7 auger holes which were unevenly spaced. Sampling again started at a higher landscape position in deep red soils and followed the catenal transect down the slope to where gleyed colours were observed along the footslopes. This catena was very similar to what was observed in *Catena 3*. Classification based on perceived colours again failed to detect any bleached topsoil horizons on the well-drained apedal subsoils (Figure 4.17) although record was made of a clear bleaching tendency at Position 5. Following instrument-measured soil colour, the topsoil at this position qualified as bleached (Figure 4.18). Similar to that observed in all the other catenas, a thickening A horizon, which in its bottom parts appeared to be more like a transition zone between the grey A and yellow B horizon, was also recorded. At Position 5 visual colour estimates did not detect bleached colours in this soil zone but upon re-measurement with the spectrophotometer an E-horizon was recorded. This resulted in the classification of a bleached Constantia soil form. What must be mentioned however is that bleaching and an E horizon was visually detected on the Kroonstad (orthic A – diagnostic E – diagnostic G) soil forms at Positions 6 and 7 (Soil classification working group 1991). Similar to *Catena 3* the unsynchronised change between top-and subsoil colour was also observed which resulted in the recorded topsoil bleaching and bleaching tendencies at Position 5 along the catena. As shown in all the other catenas, the Fe content decreased

in both the top- and subsoil horizons from higher to lower topographical positions. Interestingly, the soils along this catena revealed no observable textural differences between the A/E and B horizons and no real increase in clay content down the slope.

To summarise what was observed along the sampled catenas and similar to the record given by Van der Waals (2013), a thickening of the bleached A horizons was observed starting on the lower midslopes and becoming more pronounced until it graded into an E horizon down at the footslope positions. Although initial classification of these thickened A horizons did not recognise the presence of an E horizon toward its bottom boundary due to an inadequate colour difference and the depth limit of 350 mm (Soil classification working group 1991), the exaggerated thickening and measured bleached colours recorded in particularly *Catena 3* and *4* (Figures 4.15-4.18) justified the inclusion of an E horizon in the subsequent profile classifications. Noticeably there was no observable difference in the thickened bleached A horizons that did not exceed 350 mm in depth to those that did, implying that a similar pedogenetic process was responsible for both although the arbitrary depth boundary of 350 mm resulted in different classification outcomes. In addition, an unsynchronised change between top- and subsoil colour from red to yellow to grey resulted in a zone of overlap where bleached orthic A horizon overlying yellow-brown apedal B horizons were recorded. Although the area occupied by such a horizon sequence was relatively small it exposed a clear gap in the current South African classification system (Van der Waals 2013). Lastly, recorded colour deviations from the normal red-yellow-grey sequence were in agreement with zones of Fe depletion or accumulation along the catenas and collectively, the XRF determined Fe contents also revealed a decrease in the soil Fe content from red to yellow to grey colour zones. Field-estimated texture followed a more sporadic pattern, with textural contrasts between the A/E and B horizon not being observed in all of the catenas. Clay content did however seem to increase down the slopes. These recorded observations along all of the sampled catenas provide strong evidence towards a relationship between bleaching, topography and hydrology on the Mpumalanga Highveld.

Joffe (1949) (as cited by Huggett 1975) was amongst the first to point out that topography as a soil forming factor is a condition influencing other factors. Most noticeably is the relationship that exists between topography and soil hydrological processes (Ticehurst et al. 2007; van Tol et al. 2010; van Tol et al. 2011). If one is to consider water as the main factor influencing soil development in most environments (Wysocki et al. 2000) the association between topography and hydrology is predominantly responsible for the expression of soil characteristics within a landscape (Lin et al. 2005). However, the relationship between soil and hydrology is also interactive and although water can serve as a primary agent in soil genesis, soil characteristics also dictate hydrological processes (van Tol et al. 2010). Nonetheless, many studies have made use of soil morphological characteristics, most

noticeably colour, to indicate soil-water dynamics (Van Huyssteen & Ellis 1997; He et al. 2003; Ticehurst et al. 2007). The specific sequence of soil colours such as those recorded along the Highveld plinthic catena, which range from red higher up in the landscape through yellow in midslope positions to paler colours at the bottomlands is a prominent feature in ferrallitic environments across the globe (Peterschmitt et al. 1996). It is also widely accepted that this expression of colour is related to increasing aquic conditions and the selective dissolution of Fe oxides along such a soil toposequence (Cox et al. 1996; Peterschmitt et al. 1996; Van Huyssteen & Ellis 1997; Fey 2010). The active process within these landscapes is Fe reduction, which in more moderately drained midslope positions results in soil yellowing and in the waterlogged footslope positions causes bleaching. The process of yellowing is a consequence of both the degree of Al substitution within the clay fraction of the Fe oxides and to a lesser extent, the crystal size of these minerals (Curi & Franzmeier 1984; Jeanroy et al. 1991; Peterschmitt et al. 1996). Hematite is generally less substituted with Al in comparison to goethite, and seeing that Al restricts the dissolution of Fe oxides because it is not redox reactive (Segal & Sellers 1984; McBride 1994), hematite is more easily reduced and dissolved (Macedo & Bryant 1987). The more resistant goethite, although it can also vary in its degree of Al substitution (Peterschmitt et al. 1996), remains as a constituent on the soil particle surfaces and facilitates the expression of yellow soil colours. Where amorphous or poorly crystalline Fe oxides are present, this dissolution process is further enhanced (Jeanroy et al. 1991). Therefore the onset of wetter soil conditions is expressed through the yellowing process and more specifically the selective dissolution of hematite. Water saturation, however, triggers bleaching and the complete removal of Fe oxides (Fritsch & Fitzpatrick 1994). Peterschmitt et al. (1996) consequently proposes yellowing to be a precursor process to bleaching with yellow soils representing a soil state in which Fe oxide coatings have only partially been stripped from the soil mineral particles. The reported decrease in the Fe content of the soils down the catenal slopes provide strong evidence towards this phenomenon.

From the above-presented literature there seems to be little doubt that the catenal cross-sections presented in Figures 4.12-4.19 signifies a water-driven soil environment (Soil and Irrigation Research Institute 1987; Fey 2010). The precise dynamics of this system however remains unclear seeing that no active hydrological monitoring was done along these catenas primarily due to time and logistical constraints. However, the sequence of observed soil colours suggest Fe reduction to be the prominent genetic process within these landscapes and therefore it would appear highly likely that bleaching, even in the morphologically well-drained zones, is a result of Fe reduction. To link the reduction process to bleaching in these soil zones, one must however first obtain a better understanding of the hydrological dynamics of i) the specific top- and subsoil horizons in this study to which bleaching is applicable and ii) the soil toposequence present along these catenas.

According to the soil classification system of South Africa, yellow-brown apedal B horizons are deemed to have a higher average moisture status than their red counterparts (Soil classification working group 1991). Work done by van Huyssteen & Ellis (1997) in the Grabouw district and by Van Huyssteen et al. (2010) in the Weatherly catchment of South Africa support this notion. The study by van Huyssteen & Ellis (1997) only measured the duration of free water in profiles containing yellow-brown apedal B horizons but not the degree of water saturation that was present. Consequently, this study showed that yellow profiles contain water for longer periods of the year compared to uniform red profiles but no measure of the potential of these horizons to undergo reduction was actually determined. In the study by van Huyssteen et al. (2010) a saturation value of 70% of soil porosity was adopted as the threshold for where reduction would start to occur (van Huyssteen et al. 2005) and consequently these authors focussed more on measuring the duration of water saturation at a potential value where it would result in Fe reduction. Clear variability in the number of days that yellow-brown apedal B horizons tended to be saturated above 0.7 of porosity were recorded but their data suggested that these horizons are saturated to this level for slightly longer periods of the year (average duration of 28 days) and also tend to have a higher average degree of saturation per month compared to red apedal B horizons. These authors therefore concluded that overall yellow-brown apedal B horizons represent a wetter soil state than the uniform red variants. This is in agreement with the statement made by van Huyssteen & Ellis (1997) who, based on field observations and surveying experience, propose some yellow-brown apedal B horizons to be saturated with water for up to two months of the year.

To obtain any information in the literature about the hydrological features of diagnostic orthic A horizons that will be applicable to the topsoils present along the Highveld plinthic catenas poses a significant challenge. These diagnostic horizons occur throughout South Africa under a wide range of conditions and are therefore not completely uniform in the characteristics they exhibit (van Huyssteen 2012). To draw correlations between orthic A horizons from different regions of the country can therefore result in incorrect assumptions about the behaviour of these soils. This strengthens the opinion that without proper hydrological monitoring it is close to impossible to definitely state what hydrological forces are active in the bleached orthic A horizons that were sampled along the Highveld. However, the information that exists within the literature can still aid in formulating certain assumptions about the mechanisms at hand. The most significant piece of literature available in this regard is the work done by van Huyssteen (2012) in the Weatherly catchment of South Africa. The author focussed specifically on the hydrological aspects of orthic A horizons in this region and found that these A horizons mimicked the spectrum of subsoil hydrological conditions that were recorded. Orthic A horizons overlying E or G horizons were reported to be saturated with water for more than



six months whereas the A horizons of the well-drained red and yellow-brown apedal B subsoils were waterlogged for less than 30 days in the year. These findings are in agreement with the views of the Soil classification working group (1991), who state that there tends to be a genetic relationship between diagnostic orthic A horizons and the subsoils they overly implying similarities in their exhibited characteristics. One must not however neglect to consider that there are factors specifically applicable to topsoil horizons that will differentiate them from the subsoils they overlie such as for instance the seasonal influences of precipitation on topsoil moisture status. Van Huyssteen et al. (2010) reported that during the summer rainfall months in the Weatherly catchment, orthic A horizons are significantly wetter than the red-, yellow-brown and neocutanic B horizons they overly because of their position within the profile and their consequent direct exposure to precipitation.

For the purpose of this study the interest of course lies in the hydrological dynamics of orthic A topsoils overlying yellow-brown apedal B horizons. The above presented evidence, although proposing yellow-brown subsoils to be relatively well-drained, indicates that where the subsoil tends to be wetter, the topsoil follows this pattern. Taking into consideration the higher moisture status that has been recorded for yellow-brown apedal B's relative to red soils, it seems improbable that their topsoils should not also follow this same dynamic. Nonetheless, most of the recorded results on the moisture status of both yellow-brown apedal B subsoil horizons and diagnostic orthic A horizons reflect considerable variation (Van Huyssteen et al. 2010; Van Huyssteen 2012). To complicate the matter even more, the thickening of the bleached topsoils observable in Figures 4.11-4.18 propose that the bleached orthic A horizons recorded in the midslope positions along the sampled catenas are subject to a similar soil moisture regime as the E horizons they overly in the bottomlands. This is also the view of Van der Waals (2013). Literature on the hydrological status of diagnostic E horizons across South Africa have yielded variable results, indicating that some E horizons are considerably wetter than others (Van Huyssteen & Ellis 1997; Van Huyssteen et al. 2010). Again, this allows for no clear assumptions about the moisture status of these bleached orthic A horizons although it does allude to the fact that the potential for saturation and Fe reduction should not be overlooked. Whether the hydrological conditions that exist within the bleached topsoil horizons found on the lower midslope position of these Highveld catenas are sufficient to stimulate Fe reduction remains uncertain without any direct measurement of redox potential. It must however not be excluded based on the fact that hydromorphy and the onset of reduction is soil specific and can vary depending on the degree of water saturation, pH, soil porosity, organic matter and Fe content, temperature and the nature of the microbial population present within the soil (Van Huyssteen 2012). Taking this into consideration, topsoils generally tend to have a lower redox potential in comparison to subsoil horizons due to the higher accumulation of organic material (Wheeler et al. 1999; Rabenhorst & Parikh 2000).

What is apparent from the studies that have been reported on thus far, is that limited information regarding the hydrological links between red-yellow-grey subsoils and their accompanying topsoils in the landscape are given. This factor is probably the most applicable to understanding the hydrological dynamics of these catenas and bleaching along its midslopes. Although the generalised hydrological characteristics of yellow-brown B, orthic A and E horizons eludes to the possibility of these horizons being saturated with water to such an extent that reduction can ensue, the best evidence for Fe reduction along the midslopes of the sampled catenas will probably be exposed through a better understanding of water flow dynamics along this soil toposequence. However, Van der Waals (2013) noticed that the classification and characterisation of subsoil horizons are most commonly used to define the soil moisture regime present within a landscape, with the hydrological links between topsoil horizons along a slope often receiving little attention. South African literature providing detailed information on the topsoil moisture status along these Highveld catenas could not be found. Again, this allows one only to speculate as to how the soil-water system behaves, particularly along the upper horizons of these soil toposequences. The only real evidence that exists upon which to base assumptions about the soil's hydrological dynamics is of course morphological interpretation (Van Huyssteen & Ellis 1997; Van Huyssteen et al. 1997; He et al. 2003; Ticehurst et al. 2007). This unfortunately leaves one in a conundrum with regards to bleaching in the landscape. Nonetheless, the red-yellow-grey soil sequence is known to represent increased aquic conditions. Water from the extremely well-drained red soil zones at higher topographic positions percolates down through the midslope positions by means of subsurface lateral flow, resulting in the expressed yellow soil colours, and eventually accumulates at the bottomlands where waterlogged conditions ensues and grey soil colours develop (Van Tol et al. 2011). The observed lag in this colour sequence between top and subsoil horizons indicate that the topsoil possess a higher moisture status than the subsoil and therefore undergo these colour changes at positions higher up along the slope. This feature also seems to become apparent in the thin bleached A horizon that already starts on the lower midslope positions and thickens into an E horizon lower down. Information on the genesis of E horizons predominantly states that this zone of eluviation is the result of lateral subsurface flow (Van Huyssteen & Ellis 1997; Ticehurst et al. 2007; Van der Waals 2013; Van Tol et al. 2011) eluding to a condition where water from higher up on the catena is moving through the topsoil and saturating the soil pores to such an extent that reduction and eluviation can take place. The possibility of higher OM contents in the topsoil resulting in lower redox potentials and essentially a lower moisture requirement to enable reduction must also not be ignored as a potential influence in this system.

The question of course remains, what is essentially causing this subsurface lateral flow if the subsoil is morphologically well-drained and poses no restriction to water infiltration? Van der Waals (2013)

hypothesises that the slight textural contrast between the A and B horizon aids in stimulating lateral flow and therefore saturation lower down the slope. The results presented in this study did record some textural differences (mainly just to the extent that the subsoils were classified as luvisc), but not in all the sampled catenas (e.g. *Catena 4*) and therefore the process cannot be solely as a result of this soil feature. Rather, and in agreement with Van der Waals (personal conversation, 2014), it is proposed that due to the rainfall tendencies of the region, frequent small quantities of rain ensures that the topsoil remains wet (Van Huyssteen et al. 2010) in these midslope positions for almost the entire duration of the summer therefore causing reduction and the bleached colours. It is however not implied that no water movement will occur through these topsoils along the slope, but based on the very gradual slope gradients recorded along these catenas (Tables 4.12 and 4.13) it is assumed that water will predominantly drain vertically down the profile. The hydrological influence of the infiltrated water results in the formation of plinthic horizons at deeper soil depths. The possibility also exists that as more precipitation enters the system, the presence of antecedent soil moisture limits vertical drainage and stimulates lateral flow (Hardie et al. 2011). Consequently, two systems are ostensibly at work in the formation of the soil horizon sequences recorded along the Mpumalanga plinthic catenas: i) frequent low quantity rain showers that provide sufficient moisture to the top couple of centimetres of the soil profile to ensure that these soil horizons, with their accumulation of OM and consequent lower reduction potentials, remains wetter for longer and ii) shallow subsurface water flow and soil water fluctuations that are responsible for the red-, yellow- and plinthic B horizons at the varying depths. Throughout the summer, rainfall will drain down through the profile, providing the water responsible for subsurface flow and the genesis of the plinthic horizons. The high frequency of rain during this period also allows the topsoil to remain wet. Consequently, the 'thick' E horizon that is recorded along the footslope positions is essentially present on the midslope positions as a bleached orthic A which gradually becomes thicker further down the slope (Van der Waals 2013).

#### 4.3.3.2. *Evidence for Fe reduction: Fe characterisation*

Iron can occur in the soil environment either as a constituent ion in the clay mineral structure or as an oxide adhering to the surface of the soil mineral particles (Carroll 1958). In an oxidised form Fe is responsible for the expression of red and yellow-brown soil colour, that with the onset of Fe reduction result in the formation of redox depletions and bleaching (He et al. 2003). The oxides responsible for colour expression in the soil can range in their abundance, mineralogy and reactivity (Carroll 1958; Torrent et al. 1983; Thompson et al. 2006) which will dictate i) the nature of the colour influence of the particular Fe species, as well as ii) the chemical and physical influence of the mineral on overall soil dynamics. In general, abundance and the specific Fe mineralogy is reasoned to be of less significance in the soil environment compared to the reactivity of the Fe phases, seeing that reactivity

will directly influence Fe reduction processes (Bonnieville et al. 2004) and the cycling of various other soil constituents (Thompson et al. 2011). Iron reactivity is essentially expressed in the crystallinity of the oxide forms with poorly-crystalline Fe oxides having a greater reactive surface compared to crystalline variants, consequently being more reactive (Duiker et al. 2003; Thompson et al. 2011).

To be able to differentiate between the crystallinity and reactivity of the Fe phases present within the soil environment, different Fe extraction agents are used. Citrate-bicarbonate-dithionite (CBD) is deemed to be a strong reducing agent consequently targeting not only very reactive poorly-crystalline Fe but also more well-ordered crystalline Fe phases (McKeague & Day 1966; Loeppert & Inskeep 1996). In contrast, ammonium oxalate (AAO) extracts only the poorly-crystalline Fe species. Based on the specified Fe phases targeted by CBD and AAO, a Fe activity ratio indicative of the reactivity and degree of crystallinity of the Fe species can be calculated through  $\text{Fe}_{\text{AAO}}/\text{Fe}_{\text{CBD}}$  (Torrent 1976; Bech et al. 1997). As previously mentioned, in this study the ratio was expressed as a percentage and termed the Fe crystallinity index (CI).

The results of the different Fe extraction procedures reported lower  $\text{Fe}_{\text{AAO}}$  contents in all of the sampled horizons compared to  $\text{Fe}_{\text{CBD}}$  contents indicating that both crystalline and poorly crystalline Fe phases were present in the soils. The relationship between crystallinity and reactivity mentioned above meant that the proportions in which these different Fe oxide phases occur in the soil is of greater significance than these absolute measurements. The calculated Fe CI values were similar in both the top- and subsoil horizons at both locations, indicating that proportionally similar amounts of crystalline and poorly-crystalline Fe oxides were present in both the Western Cape and Highveld profiles. However, the CI of the topsoil Fe content tended to be higher in bleached compared to non-bleached profiles with this observed trend being more pronounced on the Highveld compared to the Western Cape soils.

In relation to Fe reduction, Thompson et al. (2006) observed that although the interchange between ferrous and ferric Fe states as a result of alternating redox cycling is well-documented, little is actually known about what the cumulative effects of such cycles are on the nature of the Fe oxides present within the soil, specifically pertaining to their crystallinity. Although some discrepancies in their laboratory trials were reported, these authors proposed that following the reduction of the available crystalline and poorly-crystalline Fe phases in the soil, the re-introduction of  $\text{O}_2$  and the consequent rapidly precipitated Ferric oxides will predominantly be short-ranged-ordered or poorly-crystalline in nature (Wahid & Kamalam 1993; Stumm & Morgan 1996). The opposite effect that was reported in the laboratory was tested in the field and following a series of field-trials by the same authors, Thompson et al. (2011) concluded that with increasing rainfall, more poorly-crystalline Fe oxides were

present at the wetter soil sites. It is therefore proposed that due to the higher Fe Cl in the topsoils of the Highveld bleached compared to non-beached profiles, more poorly crystalline Fe<sub>AAO</sub> is present which implies more novel or freshly-precipitated Fe species that are the result of a wetter soil moisture regime and alternating cycles of saturation and Fe reduction (Wahid & Kamalam 1993; Stumm & Morgan 1996; Thompson et al. 2011). These results thus provide further evidence towards the role of water saturation and reduction in the genesis of bleached A horizons on the Mpumalanga Highveld.

#### 4.3.3.3. *The probability of clay eluviation*

The soil-landscape relationships and Fe oxide characteristics of the soil profiles sampled in the Western Cape and Mpumalanga Highveld revealed significant differences with regards to the nature and occurrence of topsoil bleaching in these two locations. In summary, the lack of any landscape-related expression of bleaching in the Western Cape profiles, as well as the proportionally similar quantities of poorly-crystalline to crystalline Fe phases in both the bleached and non-bleached profiles, suggests that in contrast to bleaching on the Highveld, Fe reduction might not be the dominant or exclusive mechanism responsible for this soil phenomenon in this part of the country.

Within the literature, the other prominent pedogenetic process proposed to result in light coloured soil horizons is clay eluviation (Zaidel'man 2007; Fey 2010; Van der Waals 2013). Eluviation refers to the mobilisation and transportation of colloidal material out of a soil horizon to a zone of accumulation, where the opposite process of illuviation is responsible for the acquisition of these translocated particles in the underlying material. Collectively, clay eluviation and illuviation are referred to as lessivage (IUSS working group WRB 2007). According to Quénard et al. (2011), lessivage has generally been poorly quantified and modelled in past research and remains a somewhat controversial subject despite the description of its presence in many soil types. This can in part be attributed to the elaborate and time-consuming experimental procedures prescribed for accurately determining clay migration through a soil column (Cornu et al. 2014). Nonetheless, various soil researchers (e.g. Chittleborough 1992) and many soil classification systems including the USDA's Soil Taxonomy (Soil survey staff 2010) consider the morphological expression of argillans (or clay cutans) in a soil horizon as indisputable evidence for the translocation of clay particles. Therefore, the cutanic nature of the weakly structured subsoil horizons sampled in parts of the Western Cape strongly propose clay dispersion and translocation to be an active pedogenetic process in these soils (Soil classification working group 1991). As previously stated, the colour of all the horizons sampled in this study was first determined in the soil's natural state of aggregation i.e. as clods, where after the same procedures were repeated on fine samples. It was decided to not report the colour data on the difference between clod and fine sample colours due to the regional difference in the effect of this phenomenon and the statistical implications thereof. Visual perception could only detect slight

differences between clod and fine soil colours in some of the Western Cape soils. On the Highveld, no such differences were observed. This small set of soils in which aggregation resulted in colour differences meant that no colour effect could be statistically detected. Visual observations however provide enough reason to state that in some of the weakly structured B horizons sampled in this study, non-uniformity in colour was much more apparent in clods than in fine samples. This was the result of the presence of cutans in and around soil aggregates which caused red or yellow-brown colour variations in these subsoils, whilst bleached clay skins covering the outside of topsoil clods were also observed and resulted in a similar phenomenon. Upon crushing these clods, a more uniform and slightly different colour was observed. These features potentially provide morphological evidence for clay movement. Whether a relationship exists between clay migration and bleaching in these profiles is unknown. Unfortunately, the intricate nature of lessivage experiments also meant that directly measuring the migration of clay particles through the soil profiles sampled in this study was not possible. Instead, no direct measure of clay translocation was conducted but the focus rather was on determining the stability of the clay phase and concluding to what extent, if at all, clay dispersion occurs in bleached and non-bleached soil profiles in the Western Cape and Highveld.

Clay dispersion is usually quantified by analysing micro-aggregate stability, most commonly in the form of water dispersible clay (WDC) experiments (Seta & Karathanasis 1996; Amézketa 1999). Due to the inherent higher stability of micro-aggregates compared to macro-aggregates and clay flocculation's fundamental contribution to overall soil aggregation and structure, WDC measurements are deemed to be vital in soil stability studies (Dexter 1988; Amézketa 1999). The WDC fractions determined for top-and subsoil horizons in the Western Cape and Mpumalanga Highveld revealed two very important features of clay stability in these soils. Firstly, both top-and subsoil WDC was significantly higher in the Western Cape profiles compared to the Highveld (Figures 4.2a and b). Secondly, within the more dispersive Western Cape soils WDC was significantly higher in the bleached compared to the non-bleached topsoil horizons (Table 4.3, Figure 4.2a), with subsoil WDC also exhibiting a similar trend (Table 4.3, Figure 4.2b).

The WDC results of both the top-and subsoil horizons suggests that the Western Cape profiles are more dispersive in nature than the soils sampled up on the Highveld. Seeing that both the recorded  $Fe_{CBD}$  and  $Fe_{AAO}$  contents also tended to be higher in the Western Cape profiles compared to the Highveld (Tables 4.8 and 4.9), this represented an interesting anomaly primarily because Fe oxides are deemed to enhance structural stability and counteract clay dispersion (Le Bissonnais 1996; Seta & Karathanasis 1996; Amézketa 1999). According to Van den Broek (1989) and Duiker et al. (2003) in most studies where Fe oxides were found to have a weak stabilising effect on the soil colloidal fraction (e.g. Boggaard 1983; Bartoli et al. 1991), the authors neglected to properly characterise the Fe oxides

that were present in those studied soils. According to these authors, the distribution, particle size and crystallinity of Fe oxides will have a profound influence on their particle stabilising capacity. Duiker et al. (2003) in particular focussed on the influence of oxide crystallinity on clay stabilisation and in support of the findings by Arduino et al. (1989), concluded poorly-crystalline and therefore more reactive Fe oxides, to be more effective in aggregating and stabilising soil particles than more crystalline variants. Based on this evidence, one of the hypotheses in this study for eluviation-related bleaching in the Western Cape was that due to the mature age of the landscape and its soils (Hendey 1983), the present Fe oxides will be extremely crystalline and therefore less reactive and capable of stabilising the clay phase (Bech et al. 1997; Duiker et al. 2003). However, as presented in the previous section of this discussion, Fe oxide characterisation with regards to crystallinity and reactivity indicated that proportionally similar amounts of crystalline and poorly-crystalline Fe oxides were present in both the Western Cape and Highveld (Figures 4.7 and 4.8). Furthermore, there was no difference in the degree of crystallinity of the Fe oxides present in the Western Cape's bleached and non-bleached profiles despite the bleached variants having a more dispersive clay phase. It would therefore seem that despite the equally reactive Fe oxide fractions in the Highveld and Western Cape, the Fe oxides present in the Western Cape soils are unable to effectively stabilise the clay phase. In addition, the lack of a difference in the degree of crystallinity of the Fe oxides present in the bleached and non-bleached Western Cape profiles further disproves any crystallinity-related explanations for the weak stabilising capacity of the Fe oxides present in these soils.

The dynamic and complex nature of the clay dispersion phenomenon cautions one to solely attribute the dispersive nature of the Western Cape soils to an inability of the present oxidic minerals to provide a stabilising effect on micro-aggregate level. Although the evidence suggest that reactive and abundant Fe oxide phases are present in these distinctly dispersive soils, authors such as Amézketa (1999) advises that with regards to clay dispersion 'one must not consider one parameter without considering the interactions with the other parameters'. Similarly, authors such as Le Bissonnais (1996), Laker (2004) and Van Zijl et al. (2014) have all reported on the interactions of dispersion factors and the many processes involved with this phenomenon. To even further substantiate the complexity of clay dispersion and especially the role of Fe oxides in its dynamics, various accounts of red, Fe-rich soils that are prone to dispersion also exist. Authors such as Fedoroff (1997) and Yaalon (1997) studied red Mediterranean soils and concluded clay illuviation to be a prominent pedogenetic process in these soil environments despite the Fe oxides present at these locations. Under South African conditions, Laker & Smith (2006) reported instances of severely eroded red soils in the former Transkei region of the country. Fey (2010) in his description of oxide-rich South African soils explains that the luvic properties of some red- and yellow-brown apedal profiles also suggest that oxidic minerals do not



impart sufficient stability to clay particles to prevent their dispersion under all circumstances, a feature also noted by Van Zijl et al. (2014). Therefore, to be able to make definitive statements about the enhanced dispersive nature of the soils in the Western Cape and even more so, the bleached profiles of this province, a number of dispersion factors other than sesquioxides were investigated.

With the exception of clay mineralogy, the majority of the factors known to enhance soil dispersion were investigated in this study (Le Bissonnais 1996; Amézketa 1999; Laker 2004). Neither the EC, pH nor the organic matter fraction of the sampled profiles proved to differ between the stable Highveld and unstable Western Cape soils and were not deemed to play a role in the dispersibility of the Western Cape soils (Table 4.5, Figures 4.10 & 4.11). However, the normalised ratio of  $Fe_{CBD}$ : clay indicated that although the Western Cape soils had more Fe oxides and a greater clay fraction, proportionally more clay tended to be present per percentage Fe than in the Highveld (Figure 4.9). Although reactivity rather than the abundance of Fe oxides are deemed to be more significant in this regard (Thompson et al. 2011), the fact that more clay has to be stabilised per oxide molecule implies that the sheer abundance of clay particles could potentially overwhelm the stabilising capacity of the present Fe oxides and therefore contribute to the more dispersive nature of the Western Cape soils.

In addition to the  $Fe_{CBD}$ : clay ratio the determined exchangeable cations provided the most significant results with regards to clay dispersion in the Western Cape. Both the exchangeable sodium percentage (ESP) and Ca:Mg ratios of the sampled top- and subsoil horizons proved to differ between the Western Cape and Highveld. Figure 4.4 indicates the significantly higher ESP values that were recorded in topsoil horizons of the Western Cape profiles as well as a similar tendency in the subsoil horizons at this location. Figure 4.5 in addition also provides evidence for proportionally more Mg relative to Ca on the exchange sites of the Western Cape topsoil- and subsoil horizons compared to those of the Highveld. Laker (2004) states that low soil Ca:Mg ratios are common throughout South Africa and is more often than not related to the specific parent material from which the soils develop. In addition, the high exchangeable sodium levels (and to some extent Mg as well) commonly reported in soils along coastal regions such as the Western Cape are proposed to be a result of atmospheric accession of sea salts (Gunn & Richardson 1979).

The negative effect of high levels of exchangeable sodium on soil structural stability is well-known and accounts thereof have been made in many studies (Le Bissonnais 1996; Seta & Karathanasis 1996). This dispersing effect of sodium is related to the small and strongly hydrated nature of the monovalent cation, which upon its addition to the soil solution forms a thick film around colloidal particles thereby generating repulsive forces greater than the weak van der Waals attractive forces responsible for clay flocculation (Rengasamy & Olsson 1991). Richards (1954) (as cited by Laker 2004) reported a threshold

ESP value of 15 to be the level at which severe soil physical deterioration will start to occur. Consequently, an ESP value of 15 has been adopted and is currently still established as the critical value above which a Natric soil horizon in both the World Reference Base (IUSS working group WRB 2007) and Soil Taxonomy (Soil survey staff 2010) is defined. Despite the view that clay dispersion mainly depends on the ESP of a soil (Le Bissonnais 1996) various studies have concluded that due to the complex interactions of the different clay dispersion factors, defining specific ESP value ranges to predict soil stability is of little significance. Cresimanno et al. (1995) reported dispersion to occur at ESP levels between 2 and 5 percent whilst Van Zijl et al. (2014) found an ESP of as little as 0.67% to be sufficient in causing dispersion to the extent that it resulted in gully erosion. Although the ESP levels of the Western Cape soils by definition only represent marginal- to non-sodic conditions (Hazelton & Murphy 2007), the results from this study are in support of the statement made by Laker (2004) who concluded that the effect of sodium on the dispersion and erodibility of soils will differ and therefore no single threshold value can be adopted to quantify its influence.

The significance of the determined Ca:Mg ratio and the higher levels reported in the dispersive Western Cape soils, is that regardless of the divalent nature of both these cations, Mg has been reported to be less effective in flocculating clay particles than Ca (Rengasamy et al. 1986; Curtin et al. 1994; Dontsova & Norton 2001). Similar to sodium, the greater hydration energy of Mg over Ca means that the hydration radius of the Mg cation is greater which causes a larger separation distance between clay layers and decreases the attractive forces responsible for flocculation (Dontsova & Norton 2001). What is even more significant in the context of this study is that in soils exhibiting higher sodicity levels, Mg has been shown to exhibit enhanced negative effects on soil structural stability (Bakker & Emerson 1973; Emerson & Bakker 1973; Rengasamy et al. 1986; Curtin et al. 1994). Rahman & Rowell (1979) and Curtin et al. (1994) state that besides the more direct influence of Mg on clay stability due to the larger hydration sphere of the cation, Mg can also enhance dispersion in a more indirect manner in sodic soils. This more indirect mechanism is related to the Mg-facilitated higher adsorption of sodium on the soil exchange sites which means that it is essentially sodium that is responsible for the higher dispersion rates in these soils. Various South African studies have also reported on the dispersing effect of Mg and in the study done by Bloem & Laker (1994) Ca:Mg ratios of below one was deemed to enhance dispersion in a variety of soils sampled across the country. Additional experimental evidence for the enhanced dispersion effect of low Ca:Mg ratios in South African soils are also provided in the study done by Nel (1989) (as cited in Laker 2004). This author summarised that a low Ca:Mg ratio in combination with amongst others, a clay mineralogy consisting primarily of illite and an ESP of 3 or more, to be sufficient in causing dispersion.

Based on the above-presented literature, it is proposed that the dispersive nature of the soils sampled in the Western Cape is a result of an exchange complex comprised of primarily Na, Mg and Ca (Bakker & Emerson 1973; Emerson & Bakker 1973; Rengasamy et al. 1986; Laker 2004). Sodium and Mg are present at such levels that the dispersion influences related to their individual cation characteristics are exaggerated to such an extent that clay dispersion is a common phenomenon in the soils from this region. However, the data reported in Figures 4.4 and 4.5 present some anomalies in that although an inflated Na and Mg content can explain the difference in the WDC phase between the Western Cape and Highveld soils, none of the dispersion factors considered provided an explanation for the significantly higher WDC percentages in the bleached profiles of the Western Cape compared to the non-bleached variants. This means that the reasons for the strong relationship between clay dispersibility and bleaching in these soils is still unknown and even more significant, no certainty exist about which process precedes the other. It is entirely possible that clay dispersion is caused by the loss of Fe oxide coatings from the soil mineral particles as opposed to clay dispersion resulting in bleached soil colours. However, to be able to more definitively report on the role of clay eluviation as a potential mechanism for topsoil bleaching, it was assumed that the absence of statistically prominent dispersion factors in the bleached Western Cape profiles is related to dissimilarities in the individual profile characteristics and therefore inadequate statistical replications. As a result, each of the bleached profiles sampled in the Western Cape had to be individually re-assessed to identify potential influences that could be responsible for bleaching under circumstances other than clay eluviation and which could be responsible for the absence of statistical evidence towards eluviation-related bleaching in this Province. We proposed that lithological discontinuities between the top- and subsoil horizons of the bleached Western Cape profiles as well as the influences of podzolization are most likely responsible for this apparent anomaly.

For all of the sampled profiles the lithological continuity of the top- and subsoil horizons were calculated by means of the comparative particle size distribution (CPSD) index (Langohr et al. 1976). This index indicates the percentage of similarity between the sand fractions of the top- and subsoil horizons. One of the major shortcomings of this method however, is that index ranges indicative of the uniformity of the underlying lithology are not specified and therefore have to be adapted to the particular soils under investigation. For the purpose of this study, the CPSD index ranges were defined as follows: <90 = discontinuous; 90-94 = transitory; >94 = continuous. These ranges were based on the work from a combination of authors including Rindfleisch & Schaetzl (2001) who used a CPSD threshold value of 93 to determine lithological uniformity and Liebans (1999) who arbitrarily selected 90 as the threshold. Langohr & Van Vliet (1979) used categories where index values greater than 94 represented soils with high uniformity, 94-90 for soils that were highly similar and 90-85 for soils

considered similar. Although the CPSD method and the above defined ranges did indicate lithological discontinuities to occur in both bleached and non-bleached profiles in the Western Cape and Highveld, it was concluded that no relationship existed between the occurrence of bleaching and the distribution of binary profiles in each location. The majority of the profiles were also classified in the 90-94 CPSD value range where no clear conclusions could be made about the lithological uniformity of the profile horizons. To compensate for the influence of lithology in statistical analyses where such a small data set is used was deemed to be impractical. Despite the findings of this study, it is extremely important to state that the influence of transported material on the occurrence of topsoil bleaching in profiles across South Africa cannot be overlooked and will surely in some instances explain the presence of morphologically contrasted horizon sequences.

The process of podsolization is commonly known to cause lighter colours in topsoil horizons (Davey et al. 1975) and bleaching as a result of podsolization is recognised within the South African soil classification system (Soil classification working group 1991). This pedogenetic process by which complexes of organic acids with Al and Fe are formed and transported down a soil profile is regarded to occur only under very specific environmental, climatic and geological conditions (Lundström 2000). According to Fey (2010) podzolic soils in South Africa are most commonly found on sandy parent materials in the higher rainfall areas of the western and south-eastern Cape where the occurrence of fynbos vegetation also enhances podzol development. Profile sampling in the Western Cape therefore required a certain degree of awareness as to the possibility of observing bleached topsoils that developed as a result of podsolization. Due to the known bleaching effect of this pedogenetic process, the inclusion of a podzolic bleached profile could potentially skew the statistical output and distort evidence for alternative or novel mechanisms of bleaching.

To limit the possibility of such errors, the Fieldes and Perrott NaF field test for the detection of podzol B horizons was used (Brydon & Day 1970; Clough & Payn 1988). Two bleached profiles in particular, one on the midslopes of Papegaaiberg outside Stellenbosch (Pb 2) and the other towards the southern parts of the town of Malmesbury (Mb 1), had observable podzolic tendencies (Figure 4.20). The climatic conditions of the regions were deemed to be in line with what is required for podzol development, and although the type of vegetation that naturally occurred on the Malmesbury soil could not be identified due to human disturbances, natural fynbos was recorded at the Papegaaiberg site. The profile feature that provided the most evidence towards a podzolic soil environment was the sandy texture (>65%) and low clay contents (<15%) of both these soils (Figures 4.21 and 4.22). Morphologically, these two profiles were also the only soils sampled in the Western Cape with an undeniable yellow subsoil colour instead of the borderline red/yellow-brown matrixes observed in the other profiles. Due to their sandy nature, Pb 2 and Mb 1 also did not express a weak granular structure

similar to the other WC soil profiles. Despite the observable differences of these two profiles in relation to the other bleached profiles sampled in the Western Cape, the Fieldes and Perrott NaF field test indicated the subsoils in these profiles to not comprise of podzol B horizons (Soil classification working group 1991). Consequently, these two profiles were included in the overall statistical analyses.

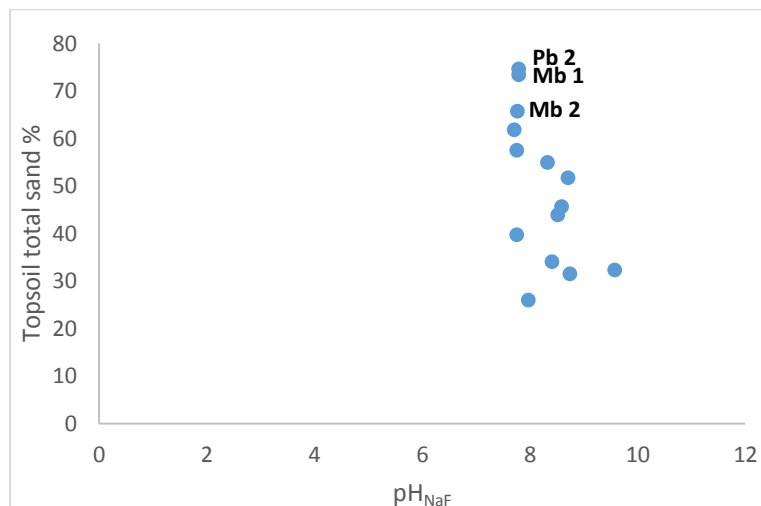
Only after no clear explanation could be provided for the more dispersive clay phase of bleached profiles in the Western Cape did the podzolic nature of profiles Pb 2 and Mb 1 seem more significant. Despite the failed detection of a podzol B horizon in these profiles by the Fieldes and Perrott NaF test, the possibility of podsolization still occurring to some extent in these soils could not be excluded. Consequently, the pH in 1 M NaF was determined for all the top- and subsoil horizons collected during the study to provide some reference. Similar to the Fieldes and Perrott field test, the reaction of NaF with hydroxyaluminium present in the soil environment causes the release of hydroxyl ions and higher pH values (Brydon & Day 1970; Alves & Lavorenti 2004). In the field test, a phenolphthalein colour development is used to indicate a rise in pH. Similarly, a higher  $\text{pH}_{\text{NaF}}$  value would imply a higher content of reactive hydroxyaluminium, which in the study by Brydon & Day (1970) was in agreement with the quantity of freshly accumulated poorly crystalline aluminosilicates characteristic of podzolic soil horizons. These authors found that all of the podzolic soils sampled in their study had a  $\text{pH}_{\text{NaF}}$  value close to 11 but established a threshold  $\text{pH}_{\text{NaF}}$  value of 10.2 to be in agreement with podzolic soil conditions detectable by means of the field test. In South Africa, Clough & Payn (1988) recorded some podzol B horizons with  $\text{pH}_{\text{NaF}}$  values smaller than 10.3 but still concluded the field test to be adequate in detecting the majority of podzolic horizons in this country. Due to the fact that the field test was negative for podzol B horizons in profiles Pb 2 and Mb 1, the expectation was that  $\text{pH}_{\text{NaF}}$  values in the extent of 10 or above would not be reported. The aim was rather to see how the  $\text{pH}_{\text{NaF}}$  of profile Pb 2 and Mb 1 compared to other profiles sampled in the Western Cape.



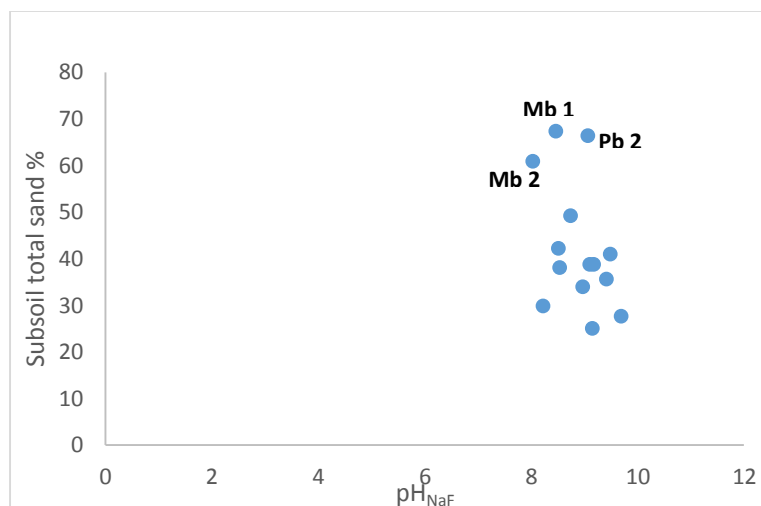


**Figure 4.20.** The bleached Western Cape profiles Pb 2 (left) and Mb 1 (right) proposed to be podzolic in nature during field sampling although the Fieldes and Perrott podzol test indicated no podzol B horizons were present.

The measured  $\text{pH}_{\text{NaF}}$  values ranged from 7.6 to 9.2 in the Highveld topsoils and from 7.6 to 9.5 in the subsoil horizons sampled at this location (Appendix 4.4). In the Western Cape, the values ranged from 7.7 to 9.6 in the topsoil and 8 to 9.7 in the subsoils. The average  $\text{pH}_{\text{NaF}}$  value for the Highveld top- and subsoils respectively was 8.5 and 8.8 with the Western Cape averages being 8.2 and 8.9. Similar to Brydon & Day (1970), a good correlation was also recorded between  $\text{pH}_{\text{NaF}}$  and  $\text{Al}_{\text{AAO}}$  verifying the reaction between NaF and supposedly poorly-crystalline and reactive aluminosilicates (Appendix 4.9). The top- and subsoil  $\text{pH}_{\text{NaF}}$  values of profile Pb 2 was 7.8 and 9.1 whilst profile Mb 1 also had a topsoil  $\text{pH}_{\text{NaF}}$  value of 7.8 but a lower subsoil value of 8.5. Although the  $\text{pH}_{\text{NaF}}$  values of these two profiles do not seem excessive, when all of the  $\text{pH}_{\text{NaF}}$  values of the Western Cape soils are plotted against their determined sand fractions (Figures 4.20 & 4.21) these profiles can be clearly distinguished.



**Figure 4.21.** The relationship between topsoil sand content and the measured pH in 1 M NaF of the Western Cape profiles. Both profiles Pb 2 and Mb 1 are indicated.



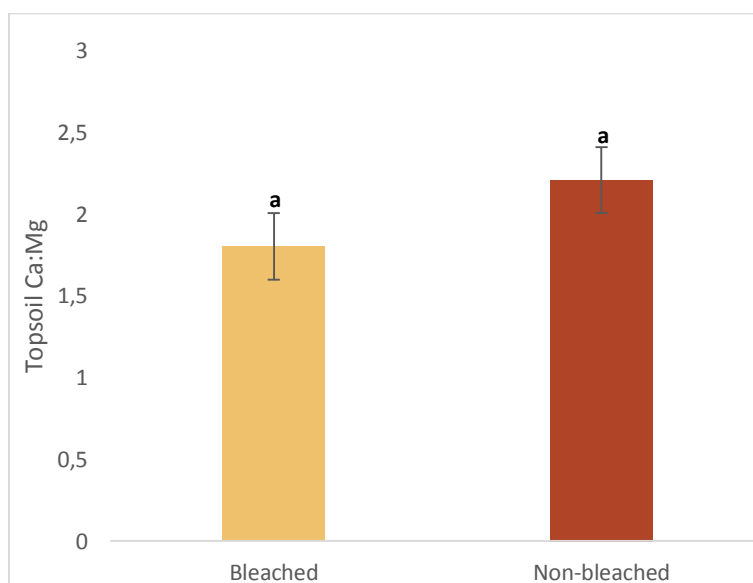
**Figure 4.22.** The relationship between topsoil sand content and the measured pH in 1 M NaF of the Western Cape profiles. Both profiles Pb 2 and Mb 1 are indicated.

The proposed presence of very reactive aluminosilicates as indicated by the relatively higher pH<sub>NaF</sub> and the substantial difference between the pH<sub>NaF</sub> values of the top- and subsoil horizons, as well as the significantly greater sand fraction in profiles Pb 2 and Mb 1 were deemed to be evidence enough to suggest potential podzolic influences in their genesis. The other soil profile which expressed a similar relationship between pH<sub>NaF</sub> and total sand content was Mb 2, another profile sampled in the Malmesbury region. Profile Mb 2, however, was not bleached nor did it exhibit any podzolic tendencies but rather had a uniform red colour in both its top- and subsoil horizons.

Upon the exclusion of the profiles Pb 2 and Mb 1 due to their suspected podzolic nature, statistical analyses were again conducted on the dispersive top- and subsoil horizons of the Western Cape



profiles. The WDC phases proved to remain significantly higher in the bleached compared to the non-bleached soils. Similarly, the determined  $\text{Fe}_{\text{CBD}}$ , clay and ESP values did not differ between the top- or subsoil horizons of the bleached and non-bleached profiles as previously reported. The exclusion of profiles Pb 2 and Mb 1 however elucidated a trend of lower Ca:Mg ratios in the topsoil horizons of bleached Western Cape profiles compared to the non-bleached variants ( $p=0.11$ ) (Figure 4.23). It would therefore seem that a greater proportion of Mg relative to Ca on the exchange sites of these soils is enhancing clay dispersion and resulting in a bleached topsoil appearance.



**Figure 4.23.** The average topsoil Ca:Mg ratio of bleached and non-bleached profiles in the Western Cape following the exclusion of profiles Pb 2 and Mb 1. Standard error bars and significance letters are indicated.

To further substantiate the probability that enhanced dispersibility of the clay phase is due to lower Ca:Mg ratios, clay mineralogy was determined for the top- and subsoil horizons of two of the bleached Western Cape profiles. As previously mentioned, Nel (1989) reported that under South African conditions a low Ca:Mg ratio will be influential to clay dispersion if illite is dominant in the clay fraction. The determined mineralogy of the two profiles indicated the soils to be well-weathered (XRD patterns provided in Appendix 4.10). A clay assemblage comprised of both kaolinite and illite as well as strongly crystalline hematite and goethite was observed. Although the XRD results undoubtedly showed that kaolinite is the dominant clay mineral in these soils, the presence of illite even as a subordinate clay mineral may enhance clay dispersion in these bleached Western Cape profiles. Amézketa (1999) makes note of the difficulty of assessing the influence of clay mineralogy on soil stability due to the mixture of clay minerals usually present within a soil and the interactions of various dispersion factors with each other. Nonetheless, the overall higher sodicity levels of the Western Cape soils in combination with the lower Ca:Mg ratio and traces of illite reported in the mineralogy of some of the

bleached profiles in this region may explain the dispersibility of the clay phase in these soils. It must be stated though that from the limited dataset generated in this study no decisive mechanism could be attained for the clay dispersion differences observed in the bleached and non-bleached soils of the Western Cape. How clay dispersion is related to bleaching therefore remains a somewhat perplexing concept.

Topsoil bleaching can be the result of a number of processes related to clay dispersion. An important distinction to make is that mobile clay is not representing a pigmentation agent that is moving out of the profile as would be the case with reduced ferrous Fe, but it would rather seem to be responsible for generating some or other condition within the soil that allows for this loss in colour. It is therefore impossible to investigate clay dispersion as a probable cause for bleaching without considering what related processes can result in a paler soil colour, and how, if at all, clay dispersion can contribute to or initiate such processes. It must be mentioned however, that if one is to consider the presence or rather absence of Fe oxides to be responsible for colour expression in these soils, no certainty exists surrounding whether mobile clay is transporting the Fe oxides or whether Fe reduction is essentially destabilising the clay phase and facilitating dispersion. Nonetheless, to essentially be able to state that clay dispersion can be responsible for topsoil bleaching, it is proposed that mobile clay would have to either i) result in a permeability contrast between the top and subsoil horizons that allows for changes in the redox condition of a soil, or ii) be acting as a carrier agent for Fe oxides.

It is widely recognised that the processes of clay eluviation and illuviation occurring continuously within a soil profile, can be responsible for a textural and structural difference between top- and subsoil horizons (Chittleborough 1992; Fritsch & Fitzpatrick 1994). Clay eluviation in the topsoil is followed by clay illuviation down through the profile which results in the establishment of a permeable topsoil layer overlying a less permeable subsoil layer and consequently the formation of saturated soil conditions during rainfall events. This would result in Fe reduction and bleaching through ferrous Fe translocation, a mechanism fairly similar to that proposed for the Highveld soils. Within this study, the evidence for Fe reduction in the Western Cape remains inconclusive seeing that although the luvic nature of many of the soil profiles did cause a slight textural contrast, this showed 1) no relationship with bleaching and 2) no detectable difference in the Fe oxide characteristics were reported between bleached and non-bleached profiles. The lack of an observable landscape-related expression of bleaching and the occurrence of bleached topsoils predominantly on well-drained landscape positions further discourages the possibility of a saturation-induced bleaching mechanism. Nonetheless, caution is advised to anyone definitively stating that Fe reduction has no or a limited role to play in topsoil bleaching in weakly structured red and yellow-brown soils of the Western Cape. No evidence was obtained in this study to enable one to make conclusive statements regarding the role of Fe

reduction and clay eluviation as independent or complementary processes responsible for bleaching in the sampled Western Cape soils.

An alternative mechanism related to clay dispersion and proposed to be responsible for bleaching, is the transportation of Fe oxides by means of clay movement (Fanning & Fanning, 1989). Although such a pigmentation process is in stark contrast to the previously-mentioned stabilising effect of Fe oxides on clay minerals, authors such as Fedoroff (1997) and Yaalon (1997) put forward a rubefaction process in the red Mediterranean soils they investigated where pigmented soil material is transported with clays to depth. They propose clay eluviation and the more general translocation of particles to be the soil forming process responsible for the expression of red colours throughout the soil profiles sampled in their studies. Although no scientific evidence was collected in this study to support such a process in the bleached soils of the Western Cape, the strong association between clay dispersion and the occurrence of bleaching implies that such a possibility cannot be disregarded.

#### **4.4 CONCLUSIONS**

Physical soil characteristics including the particle size distributions and bulk densities of the sampled soils did not show any relation to the occurrence of bleaching in topsoil horizons. Similarly, chemical parameters such as pH and EC, exchangeable acidity, the extractable Al oxide phases and the determined organic C and N contents also had no observable influence on the bleaching phenomenon in either of the two locations. The most significant findings of this broad scale investigation into the characteristics of bleached profiles in the Western Cape and Highveld, were that sampled profiles in the Western Cape possessed a significantly more dispersive clay phase compared to the Highveld soils. Clay dispersibility was even more enhanced in the bleached topsoils of this location compared to the non-bleached variants. Exchangeable basic cations may provide the explanation for this phenomenon, with elevated levels of Na and Mg being reported on the exchange sites of the Western Cape soils relative to those of the Highveld. The calculated fine clay change also tended to be higher in the Western Cape soils and even more so in the bleached profiles of this location. Although it was stipulated that the calculated fine clay change parameter does not give an absolute indication of clay translocation, the presumption that the fine clay fraction will be the most mobile in soil solution provides potential evidence of clay movement from the A to the B horizons of the sampled profiles.

The lack of a significant difference in the topsoil extractable  $\text{Fe}_{\text{CBD}}$  contents between bleached and non-bleached profiles was attributed to the nature and small size of the soil data set. Making use of the additional auger samples collected on the Highveld as part of this study and their corresponding XRF-determined Fe contents, bleached topsoil horizons proved to have a lower total Fe content

compared to their non-bleached counterparts. Fe oxides are accordingly deemed to be the main pigmentation agents in the sampled profiles and therefore the pale colouration exhibited in bleached topsoils are considered to be the result of Fe loss. Overall the Western Cape soils tended to have both a higher  $\text{Fe}_{\text{CBD}}$  and  $\text{Fe}_{\text{AAO}}$  content than the Highveld soils. The calculated Fe crystallinity index (CI) of the present Fe oxides, however, indicated that proportionally similar amounts of crystalline and poorly-crystalline Fe phases were present at both locations. The amount of poorly-crystalline Fe oxides proved to be slightly higher in bleached compared to non-bleached soils, with this trend being more pronounced on the Highveld. This proportionally greater abundance of poorly-crystalline Fe oxides was attributed to a wetter soil moisture regime and more freshly precipitated Fe in the Highveld bleached profiles.

Field observations together with the presented catenal cross-sections and the proportionally greater amounts of poorly crystalline Fe oxides that were reported for the bleached profiles in the Highveld, suggest Fe reduction to be the pedogenetic process responsible for bleached topsoil horizons overlying weakly structured subsoils in this region of South Africa. The more dispersive clay phase reported in the Western Cape soils eluded to the importance of clay eluviation as pedogenetic process in these profiles. For the Western Cape profiles, the Ca:Mg ratio tended to be lower in the bleached profiles compared to the non-bleached variants, substantiating the strong association that exists between bleaching and clay dispersion in these soils. The presented data provide no clear explanation for how clay eluviation results in bleached soil colours but the strong relationship between bleaching and clay dispersibility indicates that clay eluviation has some connection to the bleaching process in weakly structured red and yellow-brown soils of the Western Cape.

It is clear from the data presented in this chapter, that the mechanism of topsoil bleaching in weakly structured profiles is complex, especially in the soils of the Western Cape. Each profile used represents a complex amalgamation of pedogenic processes and does not serve as a true statistical replicate of a particular morphology. Thus trying to determine statistically significant differences between bleached and non-bleached soils, in order to make inferences on their different genetic pathways is challenging. That said, it can be concluded that there are real differences in weakly structured profiles in the Western Cape and Mpumalanga Highveld in terms of clay dispersibility which should provide some guidance on the classification of these soils.

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## CHAPTER 5: CONCLUSIONS AND RESEARCH SIGNIFICANCE

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### 5.1 STUDY CONCLUSIONS

- Differences were recorded in the manner with which visual perception and spectrophotometer measurements registered the Fe oxide-induced soil colours in the Munsell colour space. In general, the instrument reported significantly lower *chromas* (with up to three chroma units) and redder *hues* (by approximately one unit) compared to that which was visually determined. The eye perceived the soils to be brighter and more chromatic and, as a result, was less sensitive towards detecting bleached horizon colours. Munsell *value* corresponded well between measured and perceived colour determination techniques and was deemed to be the Munsell variable that can be most precisely determined through visual means. Due to the nature of the colour variation involved with *chroma* it was concluded that this colour variable is the most difficult to accurately determine through visual comparison to soil colour chips.
- The addition of moisture to the soil samples resulted in redder *hues*, darker *values* and lower *chromas*. The darkening effect of moisture was also observed in the lower  $L^*$  values that were reported for moist soil samples. In the case of *hue*, instrument measurements were significantly lower (redder) than that which was visually perceived whilst with Munsell *value*, the eye tended to exaggerate the darkening effect of moisture and registered significantly lower *values*. It was determined that although soil colour changes significantly from a dry to a moist state, the instrument records this effect across both Munsell *hue* and *value* whereas visual colour determination tends to predominantly register the changes in Munsell *value*.
- The discrepancies between measured and perceived colour variables were related to the inconsistencies associated with visual colour determination, which is the result of a series of physical and psychophysical influences affecting human colour perception. Under moist soil conditions, these influences coupled with the enhanced sensitivity of the instrument towards changes in the soil's reflective properties and the addition of unstandardized quantities of moisture are proposed to have further resulted in the differences that were reported between the measured and perceived colours of dry and moist soil samples.
- Visual colour determination was deemed to be sufficient for general soil classification purposes but with regards to more intricate soil colour investigations where colour's relationship to one or other soil property is under scrutiny, more precise colour measurements techniques such as the use of a spectrophotometer, are prescribed.

- In the weakly structured red and yellow-brown soil profiles sampled across parts of the Western Cape and Mpumalanga Highveld, Fe oxides proved to be the main pigmentation agents responsible for the expression of red- and yellow based colours. Results indicated that an increase in the soil Fe content resulted in a reddening of the soil sample and that in most instances the red soils that were sampled had the greatest Fe oxide contents.
- The discrepancies between visual and instrument colour measurement techniques resulted in different profile classifications and groupings. Spectrophotometer-measured colour was deemed to be more precise and consistent and was therefore used to group bleached and non-bleached profiles for subsequent statistical analysis and significance testing.
- Important observations regarding the occurrence of bleached topsoils, the type of well-drained subsoil they overlie and the landscape relationships associated with this feature were made in the Western Cape and Mpumalanga Highveld: i) Bleaching on the Mpumalanga Highveld was observed to be landscape related with bleached orthic A horizons only occurring on yellow weakly structured subsoil horizons in either midslope or footslope positions along the red-yellow-grey plinthic catenas. As a result sampling on the Mpumalanga Highveld was conducted along catenal transects. ii) The bleached profiles in the Western Cape did not seem to follow an observable landscape pattern and subsoils comprised of both redder and yellower weakly structured horizons were recorded.
- The majority of the determined chemical and physical soil properties did not differ between the Western Cape and Highveld profiles and did not show any relation to the bleaching phenomenon in either of the two locations. However, the different extractable Fe phases and the water dispersible clay (WDC) fractions of the sampled horizons proved to be significant soil features associated the occurrence of bleaching.
- The Western Cape soils possessed higher  $Fe_{CBD}$  and  $Fe_{AAO}$  contents but the amount of crystalline to poorly-crystalline Fe was proportionally similar between the two locations. Bleached profiles tended to have more poorly-crystalline Fe in the topsoil across both locations, with this trend being more pronounced in the Highveld soils. Proportionally greater amounts of poorly-crystalline Fe was deemed to be indicative of a wetter soil moisture regime and alternating cycles of Fe reduction and oxidative precipitation.
- Western Cape and Highveld profiles expressed significant differences in terms of the water dispersible clay phases of the soils. In the Western Cape, profiles tended to be more dispersive than on the Highveld, with the bleached Western Cape profiles proving to be even more unstable than the non-bleached variants. It was concluded that the Fe oxides in the Western Cape were unable to stabilise the clay phase in these locations and that the dispersive nature

of these soils can potentially be attributed to the elevated levels of Na and Mg recorded on the soil exchange sites. It was however recognised that clay dispersion and the factors responsible for its expression in the soil represents a complex interaction. An hypothesis was subsequently developed which propose that within a soil, flocculants and dispersing agents are essentially in a “tug-of-war”, where certain threshold values for each factor dictate at which stage clay will become dispersive or remain stable.

- The reported poorly-crystalline nature of the Fe oxides together with field observation and the presented catenal cross-sections, suggest Fe reduction to be the pedogenetic process responsible for bleached topsoil horizons overlying weakly structured subsoils on the Mpumalanga Highveld.
- The strong association that was recorded between bleaching and clay dispersibility in weakly structured red and yellow profiles of the Western Cape suggest clay eluviation to be a central pedogenetic process in these soils. Importantly, the presented data provided no clear explanation for how clay eluviation results in bleached soil colours and no evidence was obtained in this study to enable one to make conclusive statements regarding the role of Fe reduction and clay eluviation as independent or complementary processes responsible for bleaching in the sampled Western Cape soils.
- Lithological discontinuities and podzolization are proposed as additional potential causes for bleached topsoils overlying weakly structured subsoil horizons in South Africa but further work would need to verify this.



## 5.2 RESEARCH RECOMMENDATIONS

As with most scientific research focussed on novel topics, the outcome of this study leaves just as many questions as it provides answers. Our broad-scale investigation into the dynamics and characterisation of bleached topsoils on weakly structured subsoils in South Africa highlighted some interesting questions within the South African pedological sphere, some of which provide fascinating grounds for future research.

- **Eluviation-related bleaching in the Western Cape?** Probably the most significant question to ask in the light of the presented data, is how clay dispersibility is related to bleaching in the weakly structured red and yellow soils of the Western Cape? There is no doubt that due to the geomorphological history of the area, these soils represent a special condition. To explain this observed relationship, we proposed two potential mechanisms: 1) mobile clay is moving down the profile and in doing so, transports soil pigmenting agents such as Fe oxides out of the topsoil resulting in a bleached soil appearance, or 2) Fe reduction is responsible for the bleached colouration and the removal of Fe oxides from the topsoil thereby also destabilising the clay phase. Further research is needed to establish the dominant mechanism in this regard.
- **The significance of bleached topsoils?** Establishing the extent and presence of bleaching on weakly structured subsoil horizons in the Western Cape and Mpumalanga Highveld provides little information about the significance thereof to land-use. Based on basic soil and crop-production knowledge we know that features such as water saturation and clay dispersion are not ideal under most circumstances. How these features can influence yields or soil-use efficiency would therefore need to be determined. Bleaching's significance towards wetland delineation is another aspect deserving of consideration.
- **The role of organic matter (OM)?** Organic matter serves as the fuel for Fe reduction. Our data did not provide any conclusive evidence about its role in reduction-related bleaching. Based on the premise that topsoils will inherently have a higher OM content and therefore a lower redox potential, OM is proposed to play an essential part in reduction-related bleaching. Investigating this dynamic in more detail might therefore prove interesting.
- **The stabilising effect of Fe oxides?** Although many reports have been made of the inconsistent stabilising effect that Fe oxides have in soils, in most studies where discrepancies were recorded Fe oxides were not properly characterised. Taking this into consideration, one of the initial hypotheses of this study was that in the Western Cape, the advanced age of the soils mean that extremely crystalline Fe phases are present that are less reactive and therefore less able to stabilise the clay phase. Our characterisation of Fe into poorly-crystalline and

crystalline phases suggested that greater absolute amounts of both Fe phases were present in the very dispersive Western Cape soils but proportionally equal amounts of poorly-crystalline, or more reactive, Fe were present in the Western Cape and the stable Highveld soils. Although this disproved the hypothesis, the dispersive nature of the clay phase in the Western Cape eluded to an inability of the Fe oxides to provide a stabilising effect. Elevated levels of Na and Mg relative to Ca were suggested to be responsible for the dispersive nature of the clay phase and the hypothesis developed that within a soil, flocculants and dispersing agents are essentially in a “tug-of-war”, where certain threshold values for each factor dictate at which stage clay will become dispersive or remain stable. It is however recognised that clay dispersion and the factors responsible for its expression in the soil represents a complex interaction that is soil specific and therefore one that is even more complex to investigate through experimental means. Nonetheless, it is recommended that a more meticulous scale for quantification of Fe oxide crystallinity be used and tested in combination with a number of soil dispersion factors to investigate the influence of oxide crystallinity on the stabilising capacity of Fe oxides in the presence of different known dispersing agents.

- **Hydrological relationships along a plinthic catena?** Although various studies regarding the hydrological dynamics of red-yellow-grey soil toposequences have been conducted in different parts of the world, literature on the Highveld plinthic catenas are either not readily available or do not exist. The extensive nature with which these local catenas occur across the Mpumalanga Highveld provides the ideal opportunity to investigate how water influences soil characteristics along these toposequences. More importantly, an investigation into the hydrology of particularly the topsoil horizons that are part of these catenas can provide an indication of the degree, extent and duration of water saturation particularly in the lower midslope and footslope positions of these soil sequences. It would also be interesting to see if a difference in the moisture status of bleached and non-bleached topsoils overlying yellow-brown apedal B subsoil horizons at different positions along these catenas are present.
- **Bleaching in other parts of the country?** This study was focussed on two areas where bleached topsoils overlying weakly structured subsoil horizons had been previously recorded. Due to the variable nature of the South African soil landscape, it is not possible to make assumptions about the bleaching phenomenon across the entire country. Similar investigations into bleached topsoils overlying comparable subsoil horizons reported in other parts of the country, for example the Lowveld, would therefore also need to be conducted to better understand bleaching in the South African context.

### 5.3 BLEACHED TOPSOILS: CLASSIFICATION SIGNIFICANCE FOR SOUTH AFRICA

Although this study predominantly aimed to determine the mechanisms by which bleached topsoils develop on weakly structured subsoil horizons across two regions of their distribution, the awareness was that a better understanding of this phenomenon would also serve to direct the future classification of such profiles in the field. Important observations regarding soil colour measurements and the outcomes it can have on soil classification were also made during the study. The significance of our results towards soil classification in South Africa is as follows:

#### **Soil colour measurement**

Within the South African soil classification system, very precise Munsell colour ranges are specified as criteria used for the recognition of particular diagnostic horizons. From the colour data presented in this study it is clear that visual colour determination is far from consistent, and no means exist whereby the accuracy thereof can be determined. The significance is that in scenarios where colour is used as the defining horizon characteristic, different observers often interpret this phenomenon in a different manner resulting in different classification outcomes. Where possible, surveyors should be mindful about using colour as the definitive diagnostic criteria and rather make use of additionally specified horizon criteria to aid in the classification selection. Unfortunately, in the case of bleaching no alternative criteria exist by which to recognise this phenomenon, and our experience is that this has often lead to the misidentification of topsoil bleaching in many soil profiles. Although we do not propose establishing additional or more defining soil characteristics for the identification of bleached topsoils, we do however want to focus the attention onto the colour criteria specified for this phenomenon. In the South African soil classification system, the defined colour ranges for the recognition of a diagnostic E horizon includes more precise colours than for instance the colour criteria specified for the recognition of an albic horizon in the WRB and Soil Taxonomy systems. Re-evaluating these colours in the South African context and expanding the bleached colour selection might therefore result in fewer mistakes with regards to the identification of bleaching.

Furthermore, with specific relation to the recognition of bleached soil colours, the use of a spectrophotometer in this study indicated that where there was doubt as to whether a horizon would qualify as being bleached, the instrument tended to register the colour as bleached. Visual colour determination had a seemingly weaker ability to detect bleached soil colours. We therefore prescribe that in addition to using the existent Munsell colour criteria specified for identifying bleached topsoils, soil scientist in the field must be aware of other colour aspects of the soil profile as well. The most significant we believe, is the contrast between the A and B horizon. If a clear contrast, or even a

tendency towards a different topsoil colour exist, the soil surveyor should rather tend towards classifying the profile as bleached.

What is also important to realise is that the difference between red and yellow-brown soil colour is not always at the perceptual boundary one believes it to be. This is simply because the perception of a colour between one observer and the next, differs. Therefore, it is not proposed that the colour criteria specified in the South African classification system defining red and yellow-brown be changed, but rather that soil scientist be aware that a soil perceived to be red is sometimes per definition yellow-brown. In addition, it must be noted that the colour 7.5YR 5/3 is not allocated to neither yellow-brown apedal B nor an E horizon. The colour 7.5YR 5/3 was classified as being yellow-brown in this study.

### **Bleached topsoil horizons**

On the Mpumalanga Highveld, and as part of the red-yellow-grey plinthic catenas commonly observed in this region, bleached topsoils were recorded overlying yellow-brown apedal B horizons at midslope and footslope positions along this landscape. The observed and determined characteristics of these soils agree with the literature on red-yellow-grey soil toposequences and suggest that these Highveld catenas are a water-driven soil phenomena. It is proposed that the pedogenetic origin of these pale coloured topsoils is similar to that of the E horizons observed in comparable or lower landscape positions in this region. As a result, Fe reduction is suggested to result in the bleached colours recorded on the Mpumalanga Highveld. Based on the restricted occurrence of bleached topsoils on yellow-brown apedal B subsoil horizons and the proposed relationship of this phenomenon with water saturation and Fe reduction, the inclusion of bleached orthic A horizons as family criteria in wetter variants of the yellow-brown apedal profiles are suggested for the new edition of the South African soil classification system. This would include the Pinedene (orthic A – yellow-brown apedal B – unspecified material with signs of wetness), Avalon (orthic A - yellow-brown apedal B – soft plinthic B) and Glencoe (orthic A - yellow-brown apedal B – hard plinthic B) soil forms.

In addition, our observation regarding the bleaching phenomenon on the Highveld and its close relationship to E horizons suggest that the Constantia soil form (orthic A – diagnostic E - yellow-brown apedal B) would be a common occurrence along the lower landscape positions of these plinthic catenas. This suggests that together with the necessary perceptual shift soil scientists need to undergo surrounding the well-drained nature of the yellow-brown apedal B horizon, the perception about this soil form also requires some transformation. Fey (2010, p. 114) in his book on the *Soils of South Africa* makes record about the controversy surrounding the Constantia soil form. Here this author mentions the opposing trains of thought, where the apparent contradictory nature of an E horizon overlying a

well-drained yellow-brown apedal B horizon has resulted in some to believe the Constantia soil form needs to be disbanded and its families be allocated to a podzolic soil form (e.g. Concordia) and neocutanic profile sequences (e.g. Vilafontes). Our data suggest that such a split would be incorrect and that the Constantia soil form deserves its place in the South African soil classification system. The pedogenetic origins of the Constantia horizon sequence are not restricted to podzolization or any other process allegedly related to the development of an E horizon on neocutanic subsoils (clay eluviation?), but rather that Fe reduction can be responsible for the formation of an E horizon on yellow-brown apedal B horizons.

We believe careful consideration needs to go into the widely-accepted view that yellow-brown apedal B horizons are continuously well-drained and represent a similar drainage condition to their red counterparts. Our data suggests that this is not always the case.

The results from this study also provided significant information with regards to the classification of bleached profiles in the Western Cape. In comparison to the profiles sampled along the Mpumalanga Highveld, bleached topsoils occurred on both red and yellow weakly structured B horizons in the Western Cape. In addition, the Western Cape profiles also exhibited a significantly more dispersive clay phase. Although the morphological expression of cutans are not always as observable in some neocutanic B horizons, their origin in these soils, and in the rest of the cutanic group for that matter, is predominantly related to clay movement within the profile. Therefore, this dispersive clay phase in the bleached profiles of the Western Cape should provide some guidance on the classification of these soils. We propose that the red and yellow weakly structured subsoils underlying bleached topsoils in this area would be better classified as neocutantics, based on the instability of the clay phase and the high probability of clay movement within the profile.

If a weakly structured bleached profile outside the sequence of a red-yellow-grey catena is observed, and the possibilities of podzolization or a lithological discontinuity is ruled out, the probability exists that such pale coloured horizons has some relation to the process of clay eluviation. Bleaching can therefore serve as an indication of a more unstable profile in such circumstances, which should direct classification towards the recognition of a neocutanic B subsoil horizon.

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## APPENDICES

### **Appendix 1: Soil profile descriptions** *(all profiles were described by J.L. le Roux and C.E. Clarke)*

**Profile: Bp 1**
**Location:** Beestepan Farm, Middelburg, MP

**Lat + Long:** 25° 47' 35,376" / 29° 42' 0,468"

**Soil form & family:** Tukulu 1220

**Transitional form:** Avalon

**Terrain unit:** Midslope (3)

**Parent material solum:** Origin single, unknown, local colluvium suspected

**Slope %:** 1

**Underlying material:** Mixed lithology

**Slope shape:** Straight

**Weathering of underlying material:** Strong physical, strong chemical

**Aspect:** West

**Alteration of underlying material:** Ferruginised

**Land use:** Agronomic cash crop

**Erosion:** Not observed

**Notes:** *Profile part of catena 3. Origin unknown. Suspected transported material, contains ferruginised shale and Fe nodules. Non-uniform colour in B, soft plinthite at depth.*

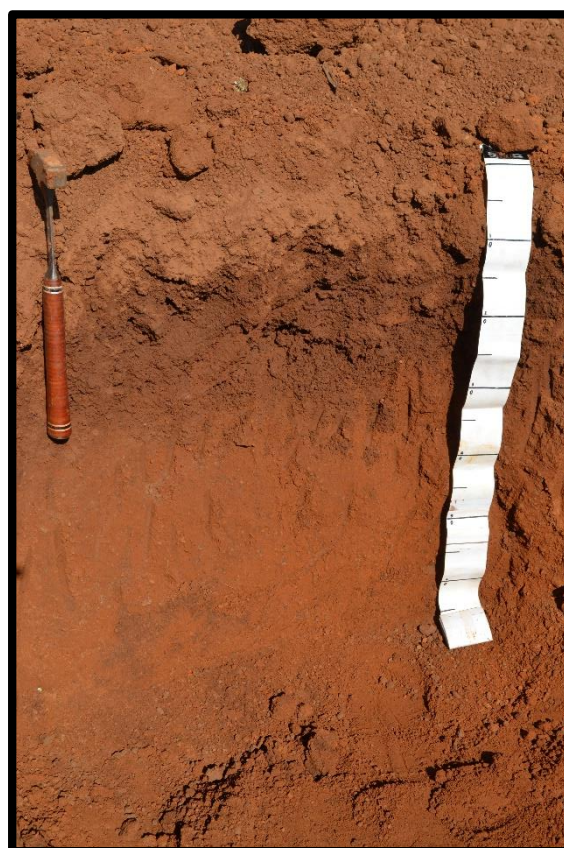
<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Bp1.1)	0-350	dry colour: yellowish red 5YR4/6; moist colour: dark reddish brown 5YR3/4; texture: sandy loam; structure: apedal; consistence: hard, friable; very few ; clear smooth transition	Orthic A
B1 (Bp1.2)	350-600	dry colour: yellowish red 5YR5/8; moist colour: yellowish red 5YR4/6; texture: sandy loam; few medium distinct red mottles; structure: weak fine subangular blocky; consistence: hard, friable; few sesquioxide cutans; many rounded gravel 2-6mm; diffuse tonguing transition.	Neocutanic B
B2	600-1500+	texture: sandy loam; common medium distinct red mottles; structure: weak fine subangular blocky; consistence: hard, friable; many rounded gravel 2-6mm.	Unspecified material, with signs of wetness



**Profile: Bp 2****Location:** Beestepan Farm, Middelburg, MP**Lat + Long:** 25° 47' 34,1874" / 29° 42' 0,3954"**Soil form & family:** Avalon 2200**Transitional form:** Tukulu**Terrain unit:** Midslope (3)**Parent material solum:** Origin single, unknown, local colluvium suspected**Slope %:** 1**Underlying material:** Mixed lithology**Slope shape:** Straight**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** West**Alteration of underlying material:** Ferruginised**Land use:** Agronomic cash crop**Erosion:** Not observed

**Notes:** Profile part of catena 3. Origin unknown. Suspected transported material, contains ferruginised shale and Fe nodules. Non-uniform colour in B, but deemed to be yellow-brown apedal. Soft plinthite at depth. Profile photo shows moisture in the A/B interface.

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Bp2.1)	0-300	dry colour: strong brown 7.5YR5/6; moist colour: brown to dark brown 7.5YR4/4; texture: sandy loam; structure: apedal; consistence: slightly hard, friable; many rounded gravel 2-6mm; clear smooth transition.	Orthic A
B1 (Bp2.2)	300-650	dry colour: strong brown 7.5YR5/8; moist colour: yellowish red 5YR4/6; texture: sandy loam; few fine faint red mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable; many rounded gravel 2-6mm; gradual smooth transition	Yellow-brown apedal B
B2	650-1500+	texture: sandy loam; common fine prominent red mottles; structure: weak fine subangular blocky; consistence: hard, friable; many rounded gravel 2-6mm.	Soft plinthic B





**Profile: Bp 3****Location:** Beestepan Farm, Middelburg, MP**Lat + Long:** 25° 47' 33,5034" / 29° 42' 0,2874"**Soil form & family:** Pinedene 2200**Transitional form:** Avalon**Terrain unit:** Footslope (4)**Parent material solum:** Origin single, unknown, local colluvium suspected**Slope %:** 0.5**Underlying material:** Mixed lithology**Slope shape:** Concave**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** West**Alteration of underlying material:** Ferruginised**Land use:** Agronomic cash crop**Erosion:** Not observed

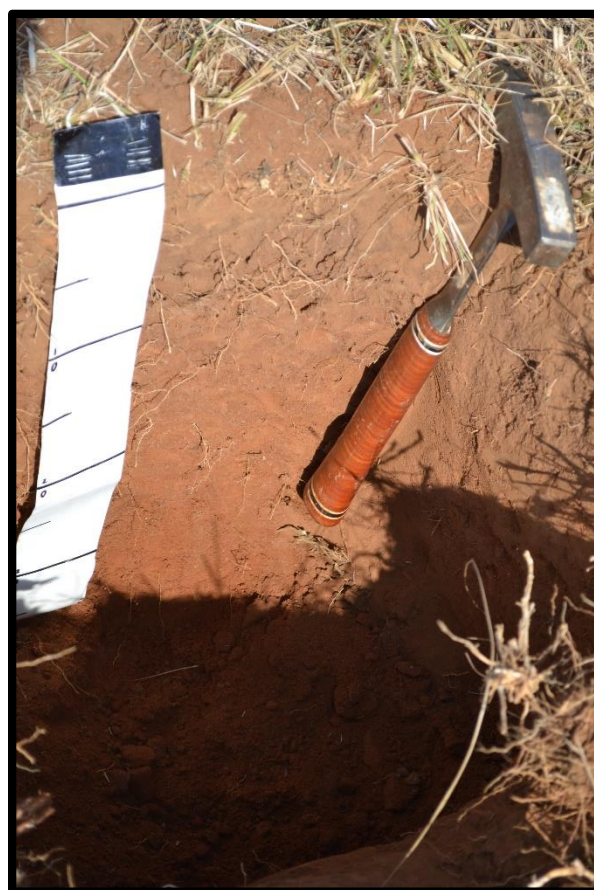
**Notes:** Profile part of catena 3. Origin unknown. Suspected transported material, contains ferruginised shale and Fe nodules. Very gradual transition between A and B. Horizon at depth few fine faint mottles, not deemed to be plinthic. Plinthic characteristic potentially more distinct at lower depths. Profile photo shows moisture in the A/B interface.

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Bp3.1)	0-300	dry colour: yellowish brown 10YR5/4; moist colour: brown to dark brown 10YR4/3; texture: sandy loam; structure: apedal; consistence: slightly hard, friable; few rounded gravel 2-6mm; diffuse smooth transition.	Orthic A
AB (Bp3.2)	300-400	dry colour: yellow 10YR7/8; moist colour: strong brown 7.5YR5/8; texture: sandy loam; structure: weak fine subangular blocky; consistence: slightly hard, friable; few rounded gravel 2-6mm; clear smooth transition	Yellow-brown apedal B
B (Bp3.3)	400-1100+	texture: sandy loam; few fine faint red and brown mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable; few rounded gravel 2-6mm.	Yellow-brown apedal B



**Profile: Br 1****Location:** Bronkhorstspuit, MP**Lat + Long:** 25° 47' 30,876" / 28° 32' 7,26"**Soil form & family:** Hutton 2200**Transitional form:** Bainsvlei**Terrain unit:** Crest (1)**Parent material solum:** Origin single**Slope %:** 1**Underlying material:** Sandstone (unspecified)**Slope shape:** Straight**Weathering of underlying material:** Strong physical**Aspect:** North-east**Alteration of underlying material:** Ferruginised**Land use:** Natural vegetation, edge of maize field**Erosion:** Not observed**Notes:** Profile part of catena 1. Classified as a Hutton, soft plinthite observed at 1500mm depth boundary.

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Br1.1)	0-150	dry colour: brown to dark brown 7.5YR4/4; moist colour: dark brown 7.5YR3/4; texture: sandy loam; structure: apedal massive; consistence: loose, loose, non-sticky, non-plastic; few fine pores; common roots; gradual smooth transition.	Orthic A
B1 (Br1.2)	150-400	dry colour: yellowish red 5YR5/6; moist colour: dark reddish brown 5YR3/4; texture: sandy loam; few fine faint brown mottles; structure: weak fine subangular blocky; consistence: soft, friable, non-sticky, non-plastic; few fine pores; common roots; gradual smooth transition.	Red apedal B
B2	400-1500	dry colour: yellowish red 5YR5/8; texture: sandy loam; structure: weak fine subangular blocky; consistence: soft, friable, non-sticky, non-plastic; few fine pores; common roots.	Red apedal B



**Profile: Br 2****Location:** Bronkhorstspuit, MP**Lat + Long:** 25° 47' 30,786" / 28° 32' 7,7994"**Soil form & family:** Avalon 2200**Transitional form:** Constantia**Terrain unit:** Midslope (3)**Parent material solum:** Origin single**Slope %:** 1.5**Underlying material:** Sandstone (unspecified)**Slope shape:** Straight**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** North-east**Alteration of underlying material:** Ferruginised**Land use:** Natural vegetation, edge of maize field**Erosion:** Not observed**Notes:** *Profile part of catena 1. Transition A/B potentially an E horizon, colour change very gradual. B2 horizon not described but classified as soft plinthic at depth 1100mm+.*

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Br2.1)	0-150	dry colour: brown 10YR5/3; moist colour: dark brown 10YR3/3; texture: loamy sand; few fine faint mottles; structure: apedal fine subangular blocky; consistence: loose, friable, non-sticky, non-plastic; few fine pores; few roots; gradual smooth transition.	Orthic A
AB (Br2.2)	150-300	dry colour: light yellowish brown 10YR6/4; moist colour: dark brown 7.5YR3/4; texture: loamy sand; few fine faint brown iron oxide mottles; structure: weak fine subangular blocky; consistence: soft, friable, non-sticky, non-plastic; few fine pores; few roots; gradual smooth transition.	Yellow-brown apedal B
B1 (Br2.3)	300-1100	dry colour: yellowish brown 10YR5/4; moist colour: dark yellowish brown 10YR4/4; texture: loamy sand; few fine faint red iron oxide mottles; structure: weak fine subangular blocky; consistence: soft, friable, non-sticky, non-plastic; few fine pores; few roots; gradual smooth transition.	Yellow-brown apedal B





**Profile: Hh 1****Location:** Old helshoogte pass, Stellenbosch, WC**Lat + Long:** 33° 55' 14,592" / 18° 54' 26,9994"**Soil form & family:** Oakleaf 1120**Transitional form:****Terrain unit:** Upper Midslope (3U)**Parent material solum:** Origin binary, local colluvium**Slope %:** 8**Underlying material:** Acid intrusive rocks (granite)**Slope shape:** Concave**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** North-east**Alteration of underlying material:** Koalinised**Land use:** Fynbos**Erosion:** Water - sheet slight, partially stabilized**Notes:** Profile close to Hh 2 and very similar. Granite PM.

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Hh1.1)	0-200	dry colour: light yellowish brown 10YR6/4; moist colour: brown to dark brown 10YR4/3; texture: silty loam; structure: weak fine crumb; consistence: hard, friable; common fine pores, common medium & coarse pores; very few angular gravel 2-6mm; bleached surface crust; many roots; clear smooth transition.	Orthic A
B1(Hh1.2)	200-400	dry colour: yellowish brown 10YR5/4; moist colour: brown to dark brown 10YR4/3; texture: loam; structure: weak fine subangular blocky; consistence: very hard, friable; common fine bleached pores, few medium & coarse pores; common clay cutans; very few angular gravel 2-6mm; common roots; gradual smooth transition.	Neocutanic B
B2	400-600+	dry colour: yellowish brown 10YR5/4; moist colour: brown to dark brown 10YR4/3; structure: weak fine subangular blocky; consistence: very hard, slightly firm; common clay cutans; very few angular gravel 2-6mm; common roots.	Neocutanic B



**Profile: Hh 2****Location:** Old helshoogte pass, Stellenbosch, WC**Lat + Long:** 33° 55' 13,44" / 18° 54' 23,6154"**Soil form & family:** Oakleaf 2120**Transitional form:****Terrain unit:** Upper Midslope (3U)**Parent material solum:** Origin binary, local colluvium**Slope %:** 8**Underlying material:** shale**Slope shape:** Convex**Weathering of underlying material:** Moderate physical, moderate chemical**Aspect:** North-east**Alteration of underlying material:** Koalinised**Land use:** Fynbos**Erosion:** Water - sheet slight, partially stabilized**Notes:** Profile close to Hh 1 and very similar. Shale PM. Shale visible at depth. Thin bleached surface crust was observed.

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Hh2.1)	0-200	dry colour: light brown 7.5YR6/4; moist colour: dark brown 7.5YR3/4; texture: silty loam; structure: apedal fine subangular blocky; consistence: hard, friable, non-sticky, non-plastic; many fine bleached pores; few angular gravel 2-6mm; bleached surface crust; many roots; clear tonguing	Orthic A
B1 (Hh2.2)	200-400	dry colour: brown 7.5YR5/4; moist colour: dark brown 7.5YR3/4; texture: silty loam; structure: weak fine subangular blocky; consistence: very hard, slightly firm, non-sticky, non-plastic; few fine normal pores, few medium & coarse pores; many clay cutans; few angular gravel 2-6mm; common roots; gradual smooth transition.	Neocutanic B
B2	400-600	structure: weak fine subangular blocky; consistence: very hard, slightly firm, non-sticky, non-plastic; few fine normal pores, few medium & coarse pores; many clay cutans; few angular gravel 2-6mm; common roots.	Neocutanic B





**Profile: Hh 3****Location:** Old helshoogte pass, Stellenbosch, WC**Lat + Long:** 33° 55' 11,028" / 18° 54' 51,3354"**Soil form & family:** Oakleaf 1220**Transitional form:****Terrain unit:** Upper midslope (3U)**Parent material solum:** Origin binary, local colluvium**Slope %:** 6**Underlying material:** Acid intrusive rocks (granite)**Slope shape:** Convex**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** North-east**Alteration of underlying material:** Ferruginised**Land use:** Fynbos, Old plantation (forestry)**Erosion:** Water - sheet slight, partially stabilized**Notes:**

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Hh3.1)	0-150	dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR5/6; texture: loam; structure: apedal fine massive; consistence: slightly hard, friable; many fine normal pores, few medium & coarse normal pores; common roots; clear smooth transition.	Orthic A
B1 (Hh3.2)	150-300	dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR4/6; texture: clay loam; structure: weak subangular blocky; consistence: very hard, slightly firm; few fine normal pores, few medium & coarse normal pores; common sesquioxide cutans; common gravel 2-6mm; few roots; gradual smooth transition	Neocutanic B
B2	300-500	structure: weak subangular blocky; consistence: very hard, slightly firm; few fine normal pores, few medium & coarse normal pores; common clay cutans; common gravel 2-6mm; few roots.	Neocutanic B



**Profile: Hh 4**
**Lat + Long:** 33° 55' 11,2434" / 18° 54' 45,468"

**Soil form & family:** Oakleaf 2120

**Terrain unit:** Upper midslope (3U)

**Slope %:** 3

**Slope shape:** landscape disturbed

**Aspect:** North

**Land use:** Fynbos, Old plantation (forestry)

**Notes:**
**Location:** Old helshoogte pass, Stellenbosch, WC

**Transitional form:**
**Parent material solum:** Origin binary, local colluvium

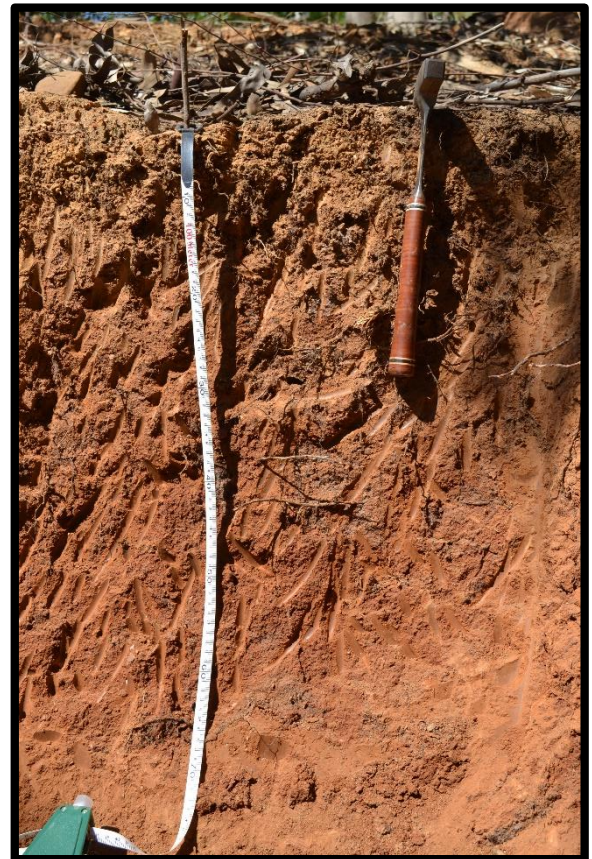
**Underlying material:** Generalised/unknown

**Weathering of underlying material:** Strong physical, strong chemical

**Alteration of underlying material:** Koalinised

**Erosion:** Water - sheet slight, partially stabilized

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Hh4.1)	0-200	dry colour: light yellowish brown 10YR6/4; moist colour: strong brown 7.5YR4/6; structure: apedal fine; consistence: slightly hard; many fine normal pores; few roots; gradual smooth transition.	Orthic A
B1 (Hh4.2)	200-400	dry colour: strong brown 7.5YR5/6; moist colour: brown to dark brown 7.5YR4/4; structure: apedal fine; consistence: hard; common fine normal pores; few clay cutans; gradual smooth transition.	Neocutanic B
B2	400-600	dry colour: yellowish red 5YR5/6; moist colour: yellowish red 5YR4/6; structure: apedal fine; consistence: hard; few fine normal pores; common clay cutans.	Neocutanic B



**Profile: Mb 1**
**Location:** Westdean cemetery, Malmesbury, WC

**Lat + Long:** 33° 27' 11,016" / 18° 42' 18,3234"

**Soil form & family:** Oakleaf 2120

**Transitional form:** Clovelly

**Terrain unit:** Upper midslope (3U)

**Parent material solum:** Origin single, local colluvium

**Slope %:** 4

**Underlying material:** Intrusive igneous rocks (unspecified)

**Slope shape:** Convex

**Weathering of underlying material:** Strong physical

**Aspect:** South-east

**Alteration of underlying material:** Ferruginised

**Land use:** Cemetery

**Erosion:** Water - sheet slight, partially stabilized, Wind - slight

**Notes:** Subsoil prominent yellow colour. Very sandy. Potentially qualify as Clovelly. Profile moist during sampling.

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Mb1.1)	0-150	dry colour: light yellowish brown 10YR6/4; moist colour: brown to dark brown 10YR4/3; texture: sandy loam; structure: apedal fine subangular blocky; consistence: friable; common fine pores; few roots; clear smooth transition	Orthic A
B1 (Mb1.2)	150-450	dry colour: reddish yellow 7.5YR6/6; moist colour: strong brown 7.5YR4/6; texture: sandy loam; structure: weak fine subangular blocky; consistence: friable; common fine pores; common clay cutans; few roots; gradual smooth transition.	Neocutanic B
B2	450-1500+	texture: sandy loam; structure: weak fine subangular blocky; consistence: friable; common fine pores; few clay cutans; few roots.	Unspecified material





**Profile: Mb 2**
**Location:** R45, Rooidraai farm, Malmesbury, WC

**Lat + Long:** 33° 24' 35,64" / 18° 41' 59,82"

**Soil form & family:** Clovelly 2200

**Transitional form:** Hutton

**Terrain unit:** Upper midslope (3U)

**Parent material solum:** Origin binary, local colluvium

**Slope %:** 3

**Underlying material:** Generalised/unknown

**Slope shape:** Convex

**Weathering of underlying material:** Strong physical

**Aspect:** North-west

**Alteration of underlying material:** Ferruginised

**Land use:** Undisturbed, Roadside vegetation

**Erosion:** Non observed

**Notes:** Subsoil borders red/yellow colour. Appears red but qualifies as yellow.

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Mb2.1)	0-200	dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: sandy loam; structure: weak fine subangular blocky; consistence: hard, friable, non-sticky, non-plastic; few fine pores; few roots; clear smooth transition.	Orthic A
B1 (Mb2.2)	200-450	dry colour: yellowish red 5YR5/6; moist colour: reddish brown 5YR4/4; texture: sandy loam; structure: weak fine subangular blocky; consistence: hard, friable, non-sticky, non-plastic; few fine pores; few clay cutans; few roots.	Yellow-brown apedal B



**Profile: Mm 1**
**Location:** Beestepan Farm, Middelburg, MP

**Lat + Long:** 25° 49' 26,4" / 29° 41' 3,444"

**Soil form & family:** Hutton 2200

**Transitional form:**
**Terrain unit:** Upper midslope (3U)

**Parent material solum:** Origin single

**Slope %:** 0.5

**Underlying material:** Sandstone (unspecified)

**Slope shape:** Straight

**Weathering of underlying material:** Strong physical, strong chemical

**Aspect:** North

**Alteration of underlying material:** Ferruginised

**Land use:** Agronomic cash crop

**Erosion:** Not observed

**Notes:** *Profile part of catena 2. Profile moist at A/B interface on photograph.*

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Mm1.1)	0-250	dry colour: reddish brown 5YR4/4; moist colour: dark reddish brown 2.5YR3/4; texture: sandy loam; structure: apedal fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; gradual wavy transition.	Orthic A
B (Mm1.2)	250-1500+	dry colour: red 2.5YR5/6; moist colour: dark reddish brown 2.5YR2.5/4; texture: sandy loam; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; gradual wavy transition.	Red apedal B





**Profile: Mm 2**
**Location:** Beestepan Farm, Middelburg, MP

**Lat + Long:** 25° 49' 25,14" / 29° 41' 3,372"

**Soil form & family:** Avalon 2200

**Transitional form:**
**Terrain unit:** Midslope (3)

**Parent material solum:** Origin single, unknown

**Slope %:** 0.5

**Underlying material:** Sandstone (unspecified)

**Slope shape:** Concave

**Weathering of underlying material:** Strong physical, strong chemical

**Aspect:** East

**Alteration of underlying material:** Ferruginised

**Land use:** Agronomic cash crop

**Erosion:** Not observed

**Notes:** Profile part of catena 2. Very gradual transition from A to B. Profile moist at A/B interface on photograph. Soft plinthite at depth (1000 mm), not described.

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Mm2.1)	0-300	dry colour: yellowish brown 10YR5/4; moist colour: dark brown 10YR3/3; structure: apedal fine; consistence: slightly hard, friable, non-sticky, non-plastic; diffuse smooth transition.	Orthic A
B1 (Mm2.2)	300-600	dry colour: red 7.5R4/6; moist colour: yellowish red 5YR4/6; few fine faint brown mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; few organic cutans; gradual smooth transition.	Yellow-brown apedal B
B2	600-1000	dry colour: red 7.5R4/6; moist colour: yellowish red 5YR4/6; few fine faint brown mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; few organic cutans; gradual smooth transition.	Yellow-brown apedal B



**Profile: Mm 3**
**Location:** Beestepan Farm, Middelburg, MP

**Lat + Long:** 25° 49' 24,9234" / 29° 41' 3,2994"

**Soil form & family:** Avalon 2200

**Transitional form:**
**Terrain unit:** Midslope (3)

**Parent material solum:** Origin single, unknown

**Slope %:** 0.5

**Underlying material:** Sandstone (unspecified)

**Slope shape:** Concave

**Weathering of underlying material:** Strong physical, strong chemical

**Aspect:** East

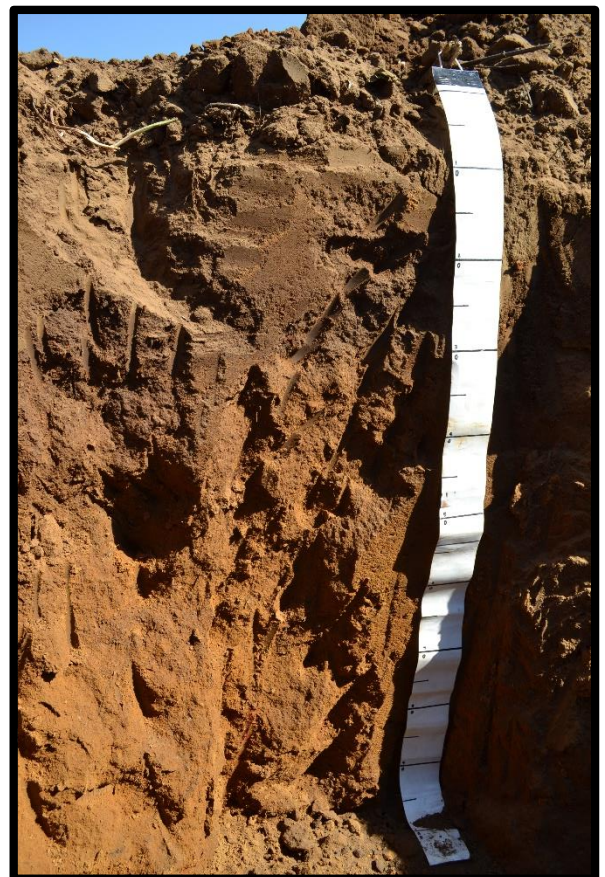
**Alteration of underlying material:** Ferruginised

**Land use:** Agronomic cash crop

**Erosion:** Not observed

**Notes:** Profile part of catena 2. Very gradual transition from A to B. Profile moist at A/B interface on photograph. Soft plinthite at depth (1200 mm), not described.

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Mm3.1)	0-300	dry colour: light yellowish brown 10YR6/4; moist colour: dark yellowish brown 10YR4/4; texture: sandy loam; structure: apedal; consistence: slightly hard, friable; gradual smooth transition.	Orthic A
B1 (Mm3.2)	300-1200	dry colour: brownish yellow 10YR6/6; moist colour: dark yellowish brown 10YR4/6; texture: sandy loam; few fine faint red mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable; diffuse smooth transition.	Yellow-brown apedal B



**Profile: Mm 4**
**Location:** Beestepan Farm, Middelburg, MP

**Lat + Long:** 25° 48' 59,5434" / 29° 40' 44,796'

**Soil form & family:** Avalon 2200

**Transitional form:**
**Terrain unit:** Footslope (3)

**Parent material solum:** Origin single, unknown, local colluvium suspected

**Slope %:** 1

**Underlying material:** Generalised/unknown

**Slope shape:** Concave

**Weathering of underlying material:** Strong physical, strong chemical

**Aspect:** North

**Alteration of underlying material:** Ferruginised

**Land use:** Agronomic cash crop

**Erosion:** Not observed

**Notes:** *Profile not sampled as part of catena.*

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Mm4.1)	0-350	dry colour: yellowish brown 10YR5/4; moist colour: dark yellowish brown 10YR4/4; texture: sandy loam; structure: apedal; consistence: hard, friable, non-sticky, non-plastic; abrupt smooth transition.	Orthic A
B1 (Mm4.2)	350-800	dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: sandy loam; few fine faint red and yellow mottles; structure: weak fine subangular blocky; consistence: hard, friable, non-sticky, non-plastic; many mixed-shape gravel 2-6mm; gradual smooth transition	Yellow-brown apedal B
B2	800-1500+	texture: sandy loam; many coarse prominent red and yellow mottles; structure: weak fine subangular blocky; consistence: hard, slightly firm, non-sticky, non-plastic; gradual smooth transition.	Soft plinthite B





**Profile: Pb 1****Location:** Papagaaiberg, Stellenbosch, WC**Lat + Long:** 33° 56' 10,9314" / 18° 50' 44,3034"**Soil form & family:** Oakleaf 2120**Transitional form:** Clovelly**Terrain unit:** Midslope (3)**Parent material solum:** Origin binary, local colluvium**Slope %:** 10**Underlying material:** Shale**Slope shape:** Straight**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** South**Alteration of underlying material:** Koalinised**Land use:** Fynbos, Old plantation (forestry)**Erosion:** Non-observed**Notes:** Profile was moist when sampled, appeared uniform in colour but following drying cutanic characteristics became apparent.

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Pb1.1)	0-150	dry colour: strong brown 7.5YR5/6; moist colour: dark brown 7.5YR3/4; texture: silty loam; structure: weak fine crumb; consistence: friable; many fine normal pores, common medium & coarse normal pores; few gravel 2-6mm; surface crust; many roots; gradual smooth transition.	Orthic A
B1 (Pb1.2)	150-300	dry colour: strong brown 7.5YR4/6; moist colour: brown to dark brown 7.5YR4/4; texture: clay loam; structure: weak medium crumb; consistence: friable; common fine normal pores, few medium & coarse normal pores; few clay cutans; few gravel 2-6mm; gradual smooth transition.	Neocutanic B
B2	300-900	moist colour: strong brown 7.5YR4/6; structure: weak medium crumb; consistence: friable; common fine normal pores, few medium & coarse normal pores; few clay cutans; few gravel 2-6mm.	Unspecified material



**Profile: Pb 2****Location:** Papagaaiberg, Stellenbosch, WC**Lat + Long:** 33° 56' 16,9794" / 18° 50' 35,3034"**Soil form & family:** Clovelly 2200**Transitional form:** Constantia**Terrain unit:** Upper midslope (3U)**Parent material solum:** Origin binary, local colluvium**Slope %:** 2**Underlying material:** Shale**Slope shape:** Convex**Weathering of underlying material:** Unknown**Aspect:** South**Alteration of underlying material:** Normal weathering**Land use:** Fynbos, Old plantation (forestry)**Erosion:** Water - sheet slight, stabilized.

**Notes:** Profile very sandy and prominent yellow colour was observed. Suspected podzol B, but did not qualify by means of the Fieldes & Perrott field test.

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Pb2.1)	0-150	dry colour: light yellowish brown 10YR6/4; moist colour: yellowish brown 10YR5/4; texture: sandy loam; structure: apedal single grain; consistence: slightly hard, friable; common fine normal pores, many medium & coarse normal pores; bleached surface crust; many roots; abrupt smooth	Orthic A
B1 (Pb2.2)	150-300	dry colour: reddish yellow 7.5YR6/6; moist colour: strong brown 7.5YR5/6; texture: sandy loam; structure: apedal single grain; consistence: slightly hard, firm; many fine normal pores, many medium & coarse normal pores; common roots; gradual smooth transition.	Yellow-brown apedal B
B2	300-1500	dry colour: yellow 10YR7/8; moist colour: strong brown 7.5YR5/8; texture: sandy loam; structure: apedal single grain; consistence: slightly hard, firm; many fine normal pores, many medium & coarse normal pores; common roots; gradual smooth transition.	Yellow-brown apedal B



**Profile: Pb 3****Location:** Papagaaiberg, Stellenbosch, WC**Lat + Long:** 33° 56' 0,6354" / 18° 50' 57,084"**Soil form & family:** Tukulu 1120**Transitional form:****Terrain unit:** Upper midslope (3U)**Parent material solum:** Origin binary, local colluvium**Slope %:** 25**Underlying material:** Shale**Slope shape:** Convex**Weathering of underlying material:** Unknown**Aspect:** South**Alteration of underlying material:** Normal weathering**Land use:** Fynbos, Old plantation (forestry)**Erosion:** Water - sheet slight, stabilized.**Notes:** Profile a little more structured but still qualifies as weak grade.

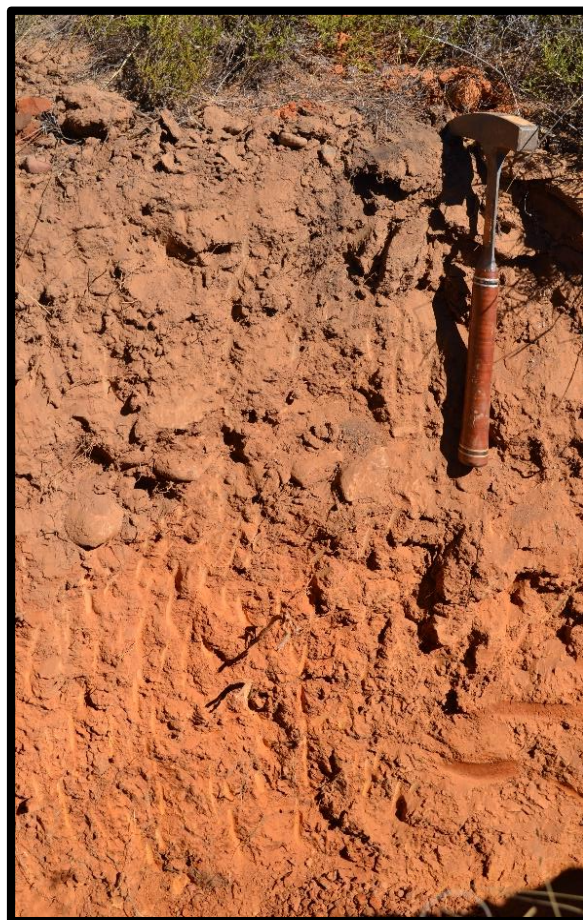
<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Pb3.1)	0-200	dry colour: light yellowish brown 10YR6/4; moist colour: brown to dark brown 7.5YR4/4; texture: silty loam; structure: weak fine subangular blocky; consistence: slightly hard, friable; many fine normal pores, few medium & coarse pores, medium cracks; bleached surface crust; common roots; clear smooth transition.	Orthic A
B1 (Pb3.2)	200-400	dry colour: reddish yellow 7.5YR6/6; moist colour: reddish brown 5YR4/4; texture: silty loam; structure: weak medium subangular blocky; consistence: very hard, slightly firm; few fine normal pores, few medium & coarse bleached pores, medium cracks; common clay cutans; common roots; gradual smooth transition.	Neocutanic B
B2	400-1100	dry colour: yellowish red 5YR5/6; moist colour: yellowish red 5YR4/6; texture: silty clay loam; structure: weak medium subangular blocky; consistence: very hard, slightly firm; few fine normal pores, few medium & coarse pores, medium cracks; common clay cutans; few roots; gradual	Neocutanic B
C	1100-1500+	texture: silty clay loam; few medium faint grey and yellow oxidized iron oxide mottles; structure: moderate medium subangular blocky; common clay cutans; few roots; gradual smooth transition.	Unspecified material, with signs of wetness





**Profile: Rk 1****Location:** Ribbokkop Farm, Ceres, WC**Lat + Long:** 33° 18' 8,532" / 19° 37' 2,208"**Soil form & family:** Tukulu 2110**Transitional form:****Terrain unit:** Lower Footslope (4L)**Parent material solum:** Origin binary, local colluvium**Slope %:** 4**Underlying material:** shale**Slope shape:** Concave**Weathering of underlying material:** Strong physical, moderate chemical**Aspect:** North-east**Alteration of underlying material:** koalinised**Land use:** Fynbos (Renosterveld)**Erosion:** Water – sheet slight, stabilised**Notes:** *Large colour variations observed in A. Clear cutans in B, some bleached.*

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Rk1.1)	0-250	dry colour: brown 7.5YR5/4; moist colour: brown to dark brown 7.5YR4/4; texture: sandy loam; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky; few fine normal pores, few medium & coarse normal pores; very few mixed-s	Orthic A
B1 (Rk1.2)	250-550	dry colour: yellowish red 5YR5/8; moist colour: yellowish red 5YR4/6; texture: sandy clay loam; structure: weak fine subangular blocky; consistence: hard, friable, non-sticky; few fine normal pores, few medium & coarse normal pores; common clay cutans; fe	Neocutanic B
B2	550-1500+	dry colour: red 2.5YR4/8; moist colour: yellowish red 5YR5/8; texture: clay; common medium distinct yellow reduced iron oxide mottles; common medium faint yellow mottles; structure: moderate medium angular blocky; consistence: hard, friable, slightly stic	Unspecified material, with signs of wetness





**Profile: Rk 2**
**Lat + Long:** 33° 18' 8,532" / 19° 36' 31,86"

**Soil form & family:** Tukulu 2120

**Terrain unit:** Lower Midslope (3L)

**Slope %:** 8

**Slope shape:** Concave

**Aspect:** North-east

**Land use:** Fynbos (Renosterveld)

**Location:** Ribbokkop Farm, Ceres, WC

**Transitional form:**
**Parent material solum:** Origin binary, local colluvium

**Underlying material:** Mixed lithology

**Weathering of underlying material:** Unknown

**Alteration of underlying material:** koalinised

**Erosion:** Water – sheet slight, stabilised

**Notes:**

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Rk2.1)	0-300	dry colour: brown 10YR5/3; moist colour: brown to dark brown 7.5YR4/4; texture: sandy loam; structure: apedal fine massive; consistence: slightly hard; few fine normal pores, few medium & coarse normal pores, fine cracks; very few mixed- shape coarse gravel 6- 25mm; bleached surface crust; few roots; clear wavy transition.	Orthic A
B1 (Rk2.2)	300-700	dry colour: reddish yellow 5YR6/6; moist colour: yellowish red 5YR4/6; texture: loam; structure: weak fine angular blocky; consistence: hard; few fine normal pores, few medium & coarse normal pores, fine cracks; few clay cutans; very few mixed- shape coarse gravel 6- 25mm; common roots; clear wavy transition.	Neocutanic B
B2	700- 1500+	dry colour: strong brown 7.5YR5/8; common medium distinct grey and yellow mottles; structure: weak fine angular blocky; consistence: hard; few fine bleached pores, few medium & coarse bleached pores, fine cracks; very few mixed-shape stones 25- 75mm; few roots.	Unspecified material, with signs of wetness



**Profile: Rk 3**
**Location:** Ribbokkop Farm, Ceres, WC

**Lat + Long:** 33° 18' 33,408" / 19° 36' 0,432"

**Soil form & family:** Oakleaf 1220

**Transitional form:**
**Terrain unit:** Lower Midslope (3L)

**Parent material solum:** Origin single, local colluvium

**Slope %:** 7

**Underlying material:** Mixed lithology

**Slope shape:** Straight

**Weathering of underlying material:** Unknown

**Aspect:** South-west

**Alteration of underlying material:**
**Land use:** Fynbos (Renosterveld)

**Erosion:** Water – sheet slight, stabilised

**Notes:**

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Rk3.1)	0-300	dry colour: strong brown 7.5YR4/6; moist colour: reddish brown 5YR4/4; texture: sandy loam; structure: weak fine subangular blocky; consistence: slightly hard; common fine normal pores; common roots; gradual smooth transition.	Orthic A
B1 (Rk3.2)	300-600	dry colour: yellowish red 5YR5/6; moist colour: reddish brown 5YR4/4; texture: loam; structure: weak fine subangular blocky; consistence: hard; few fine normal pores, common medium & coarse pores; few clay cutans; common roots; clear smooth transition.	Neocutanic B
B2	600-1500+	dry colour: red 2.5YR5/6; moist colour: red 2.5YR4/6; common red iron oxide mottles; structure: weak subangular blocky; common clay cutans; few roots.	Unspecified material





**Profile: Rk 4**
**Location:** Ribbokkop Farm, Ceres, WC

**Lat + Long:** 33° 18' 33,588" / 19° 35' 57,732"

**Soil form & family:** Oakleaf 1220

**Transitional form:**
**Terrain unit:** Upper Midslope (3U)

**Parent material solum:** Origin single, local colluvium

**Slope %:** 7

**Underlying material:** Mixed lithology

**Slope shape:** Convex

**Weathering of underlying material:** Unknown

**Aspect:** South

**Alteration of underlying material:**
**Land use:** Fynbos (Renosterveld)

**Erosion:** Water – sheet slight, stabilised

**Notes:**

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Rk4.1)	0-250	dry colour: strong brown 7.5YR5/6; moist colour: brown to dark brown 7.5YR4/4; texture: loam; structure: weak subangular blocky; consistence: slightly hard; common fine normal pores, few medium & coarse pores; very few mixed-shape gravel 2-6mm; common roots; gradual transition.	Orthic A
B1 (Rk4.2)	250-650	dry colour: strong brown 7.5YR5/6; moist colour: reddish brown 5YR4/4; texture: loam; structure: weak subangular blocky; consistence: slightly hard; few fine normal pores; few sesquioxide cutans; very few mixed-shape gravel 2-6mm; few roots; gradual transition.	Neocutanic B
B2	650-1500+	structure: weak; consistence: soft; few fine normal pores; few roots.	Unspecified material



**Profile: *Us 1***
**Lat + Long:** 26° 12' 3,24" / 29° 49' 44,5074"

**Soil form & family:** Hutton 2200

**Terrain unit:** Upper midslope (3U)

**Slope %:** 4

**Slope shape:** Convex

**Aspect:** North-west

**Land use:** Agronomic cash crop

**Notes:** *Profile part of catena 4.*
**Location:** Uys Farm, Hendrina, MP

**Transitional form:**
**Parent material solum:** Origin single, unknown

**Underlying material:** Sandstone (unspecified)

**Weathering of underlying material:** Strong physical, strong chemical

**Alteration of underlying material:** Ferruginised

**Erosion:** Not observed

Horizon (number in brackets refer to sample number)	Depth (mm)	Description	Diagnostic horizon
A (Us1.1)	0-350	dry colour: reddish brown 5YR5/4; moist colour: dark reddish brown 5YR3/3; texture: sandy loam; consistence: slightly hard, friable, non-sticky non-plastic; few mixed-shape gravel 2-6mm; gradual smooth transition.	Orthic A
B (Us1.2)	350-1500+	dry colour: yellowish red 5YR5/8; moist colour: red 2.5YR4/8; texture: sandy loam; consistence: slightly hard, friable, non-sticky, non-plastic; few mixed-shape gravel 2-6mm; gradual smooth transition.	Red apedal B





**Profile: Us 2****Location:** Uys Farm, Hendrina, MP**Lat + Long:** 26° 12' 0,6474" / 29° 49' 42,312"**Soil form & family:** Avalon 2100**Transitional form:** Glencoe**Terrain unit:** Lower midslope (3L)**Parent material solum:** Origin single, unknown**Slope %:** 4**Underlying material:** Sandstone (unspecified)**Slope shape:** Straight**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** North-west**Alteration of underlying material:** Ferruginised**Land use:** Agronomic cash crop**Erosion:** Not observed**Notes:** *Profile part of catena 4. Plinthite borderline between soft and hard.*

Horizon	Depth (mm)	Description	Diagnostic horizon
A (Us2.1)	0-350	dry colour: yellowish brown 10YR5/4; moist colour: brown to dark brown 10YR4/3; texture: sandy loam; structure: apedal; consistence: slightly hard, friable, non-sticky, non-plastic; gradual smooth transition.	Orthic A
B1 (Us2.2)	350-1000+	dry colour: yellowish brown 10YR5/6; moist colour: dark yellowish brown 10YR4/4; texture: sandy loam; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; few gravel 2-6mm; gradual wavy transition	Yellow-brown apedal B
B2	1000-1500+	texture: sandy loam; many coarse prominent red mottles; structure: weak fine subangular blocky; consistence: hard, slightly firm, non-sticky, non-plastic; continuous strong nodular pan cementation of iron & manganese oxides.	Soft plinthic B



**Profile: Us 3****Location:** Uys Farm, Hendrina, MP**Lat + Long:** 26° 11' 59,994" / 29° 49' 41,736"**Soil form & family:** Avalon 1200**Transitional form:** Constantia**Terrain unit:** Lower midslope (3L)**Parent material solum:** Origin single, unknown**Slope %:** 4**Underlying material:** Sandstone (unspecified)**Slope shape:** Concave**Weathering of underlying material:** Strong physical, strong chemical**Aspect:** North-west**Alteration of underlying material:** Ferruginised**Land use:** Agronomic cash crop**Erosion:** Not observed**Notes:** *Profile part of catena 4. Gradual transition between A and B. Signs of wetness (mottles) grade into soft plinthite with depth.*

<b>Horizon</b> (number in brackets refer to sample number)	<b>Depth (mm)</b>	<b>Description</b>	<b>Diagnostic horizon</b>
A (Us3.1)	0-350	dry colour: greyish brown 10YR5/2; moist colour: very dark greyish brown 10YR3/2; texture: sandy loam; structure: apedal; consistence: slightly hard, friable, non-sticky, non-plastic; diffuse wavy transition.	Orthic A
AB (Us3.2)	350-450	dry colour: very pale brown 10YR7/4; moist colour: brownish yellow 10YR6/6; texture: sandy loam; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; few organic cutans; few rounded gravel 2-6mm; diffuse wavy transition.	Yellow-brown apedal B
B1	450-800	moist colour: brownish yellow 10YR6/8; texture: sandy loam; few medium faint red mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; few rounded gravel 2-6mm; gradual smooth transition.	Yellow-brown apedal B
B2	800-1500+	texture: sandy loam; common medium distinct red mottles; structure: weak fine subangular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; few rounded gravel 2-6mm.	Soft plinthic B





**Profile: W3****Location:** Welgevallen, Stellenbosch, WC**Lat + Long:** 33° 57' 5.2" / 18° 52' 16.8"**Soil form & family:** Oakleaf 2120**Transitional form:****Terrain unit:** Upper Midslope (3U)**Parent material solum:** Origin single, local colluvium**Slope %:** 6**Underlying material:** Mixed lithology**Slope shape:** Convex**Weathering of underlying material:** NA**Aspect:** North-east**Alteration of underlying material:****Land use:** Abandoned field/disturbed land**Erosion:** Water - sheet slight, stabilized**Notes:**

Horizon	Depth (mm)	Description	Diagnostic horizon
A (W31.1)	0-300	Moist state; dry colour: light yellowish brown 10YR6/4; moist colour: brown to dark brown 7.5YR4/4; texture: medium sandy clay loam; structure: apedal massive; consistence: hard, firm; few fine normal pores, few medium	Orthic A
B1 (W31.2)	300-600	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: yellowish red 5YR4/6; texture: sandy clay loam; few medium distinct red and brown iron oxide mottles; structure: weak medium subangular blocky; consistence: hard, slightly firm; few fine normal pores, few medium & coarse normal pores; few clay cutans; few roots;	Neocutanic B
B2	600-900	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: yellowish red 5YR5/6; texture: sandy clay; common medium distinct red and brown iron oxide mottles; structure: weak fine subangular blocky; consistence: hard, slightly firm; few fine normal pores, few medium & coarse normal pores; few clay cutans; few roots;	Neocutanic B
B3	900-1200+	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: yellowish red 5YR5/8; texture: sandy clay; many medium distinct red and brown iron oxide mottles; structure: weak fine subangular blocky; consistence: hard, slightly firm; few fine normal pores, few medium & coarse normal pores; few clay cutans; few roots.	Neocutanic B



**Appendix 2.1.** A comparison between extractable citrate-bicarbonate-dithionite (CBD) Fe in milled and unmilled soil from a randomly selected subsample.

Sample	$\text{Fe}_{\text{CBD}}$ (%)	
	Unmilled	Milled
<i>Br 1.2</i>	1.67	1.64
<i>Mn 1.1</i>	1.57	1.54
<i>Hh 3.1</i>	2.45	2.55
<i>Bp 2.1</i>	1.88	2.40
<i>Rk 3.1</i>	2.00	2.08



Photographic evidence of the Fe concretions (ferruginised rock and gravel fragments) recorded along catena 3, which included horizon Bp 2.1. This was proposed to result in higher  $\text{Fe}_{\text{CBD}}$  values in the milled sample. All of the Bp soils contained similar fragments.

**Appendix 3.1.** Spearman-r correlation values indicating the relationships between all the recorded soil and colour variables.

	Co Clay (%)	Fi Clay (%)	Total Clay (%)	Bulk Density (Kg.m-1)	pH (H2O)	pH (KCl)	EC (mS/m)	CBD Fe (%)	AAO Fe (%)	CBD Al (%)	AAO Al (%)	Fe Cl	Al Ratio (%)	CBD Fe:Clay	Coarse Fragments %	Very CoSa (%)	CoSa (%)
<b>Perceived Hue (Clod)</b>	-0,40	-0,34	-0,42	-0,16	0,06	0,13	0,00	-0,64	-0,41	-0,27	- 0,36	0,45	0,08	-0,45	-0,25	-0,13	0,13
<b>Perceived Value (Clod)</b>	0,07	-0,16	0,03	-0,28	-0,03	-0,07	0,26	-0,09	0,01	0,06	- 0,10	0,09	-0,10	-0,27	0,05	0,23	-0,08
<b>Perceived Chroma (Clod)</b>	0,39	0,57	0,45	0,02	0,06	0,00	0,06	0,61	0,44	0,42	0,50	-0,37	-0,14	0,35	0,26	0,26	-0,13
<b>Perceived Hue</b>	-0,43	-0,42	-0,47	-0,16	-0,03	0,04	0,11	-0,56	-0,31	-0,23	- 0,32	0,38	0,10	-0,21	-0,09	0,02	0,17
<b>Perceived Value</b>	-0,05	-0,24	-0,08	-0,05	-0,05	-0,06	0,18	-0,20	-0,07	-0,02	- 0,11	0,21	-0,03	-0,27	0,02	0,12	-0,04
<b>Perceived Chroma</b>	0,44	0,63	0,50	0,15	0,14	0,11	0,17	0,54	0,34	0,49	0,50	-0,38	-0,26	0,17	0,27	0,31	-0,09
<b>Measured Hue</b>	-0,22	-0,28	-0,24	-0,26	-0,09	0,00	-0,05	-0,26	-0,14	-0,05	- 0,10	0,13	-0,01	-0,10	-0,12	-0,21	-0,08
<b>Measured Value</b>	0,16	-0,39	0,08	-0,11	-0,10	-0,12	0,13	-0,04	0,16	0,16	- 0,04	0,20	-0,22	-0,18	0,27	0,17	-0,20
<b>Measured Chroma</b>	0,62	0,22	0,58	0,02	-0,19	-0,29	0,06	0,47	0,57	0,57	0,40	-0,09	-0,36	0,03	0,36	0,02	-0,37
<b>L*</b>	0,41	-0,22	0,33	-0,23	-0,21	-0,33	0,02	0,12	0,30	0,35	0,12	0,15	-0,33	-0,25	0,27	0,02	-0,40
<b>a*</b>	0,71	0,56	0,73	0,06	-0,08	-0,18	0,03	0,75	0,58	0,59	0,59	-0,38	-0,26	0,19	0,29	0,11	-0,32
<b>b*</b>	0,63	0,15	0,59	-0,15	-0,24	-0,33	0,08	0,42	0,53	0,63	0,44	-0,05	-0,44	-0,11	0,32	0,09	-0,45

**Appendix 3.1 (Continued).** Spearman-r correlation values indicating the relationships between all the recorded soil and colour variables.

	MeSa (%)	FiSa (%)	Very FiSa (%)	Total Sand (%)	CoSi (%)	FiSi (%)	Total Silt (%)	WDC	SDC	WDC (%)	Ca (cmolc.kg-1)	Mg (cmolc.kg-1)	Na (cmolc.kg-1)	K (cmolc.kg-1)	Exchangeable Basic cations (cmolc.kg-1)
<b>Perceived Hue (Clod)</b>	0,37	0,42	0,06	0,38	-0,12	-0,36	-0,32	-0,34	-0,37	-0,15	-0,01	-0,11	-0,24	-0,19	-0,08
<b>Perceived Value (Clod)</b>	-0,15	-0,11	-0,13	-0,19	0,20	0,18	0,23	0,23	0,12	0,21	-0,15	-0,04	0,32	-0,09	-0,13
<b>Perceived Chroma (Clod)</b>	-0,30	-0,14	-0,04	-0,28	0,24	0,18	0,25	0,24	0,65	-0,12	0,02	0,15	0,08	-0,14	0,08
<b>Perceived Hue</b>	0,32	0,25	-0,09	0,27	0,03	-0,22	-0,17	-0,25	-0,43	0,00	-0,03	-0,13	-0,18	-0,03	-0,13
<b>Perceived Value</b>	-0,04	0,01	-0,14	-0,08	0,17	0,08	0,10	0,11	0,03	0,11	-0,10	-0,07	0,16	-0,17	-0,08
<b>Perceived Chroma</b>	-0,30	-0,09	-0,03	-0,25	0,18	0,15	0,20	0,24	0,68	-0,14	0,04	0,06	0,15	-0,10	0,10
<b>Measured Hue</b>	0,13	0,05	-0,13	0,02	0,20	-0,06	-0,01	-0,07	-0,30	0,04	-0,06	0,05	-0,21	0,02	-0,08
<b>Measured Value</b>	-0,32	-0,33	-0,24	-0,40	0,32	0,47	0,47	0,43	0,10	0,45	-0,17	0,03	0,52	-0,02	-0,11
<b>Measured Chroma</b>	-0,58	-0,50	-0,11	-0,61	0,31	0,54	0,58	0,61	0,58	0,34	-0,33	0,23	0,50	-0,18	-0,16
<b>L*</b>	-0,52	-0,49	-0,20	-0,59	0,36	0,62	0,64	0,61	0,29	0,54	-0,36	0,04	0,68	-0,06	-0,23
<b>a*</b>	-0,56	-0,42	0,00	-0,58	0,33	0,46	0,50	0,53	0,79	0,10	-0,17	0,17	0,39	-0,13	-0,02
<b>b*</b>	-0,60	-0,47	-0,16	-0,68	0,42	0,62	0,66	0,66	0,65	0,33	-0,40	0,09	0,62	-0,18	-0,23

**Appendix 3.1 (Continued).** Spearman-r correlation values indicating the relationships between all the recorded soil and colour variables.

	Al (cmolc.kg-1)	H (cmolc.kg-1)	Exchangeable acidity (cmolc.kg-1)	ECEC	ESP	Ca:Na ratio	Ca:Mg ratio	%N	%C	C:N ratio
<b>Perceived Hue (Clod)</b>	-0,15	-0,18	-0,15	-0,36	0,02	0,07	0,10	-0,27	-0,09	0,14
<b>Perceived Value (Clod)</b>	0,07	0,12	0,06	-0,06	0,33	-0,28	-0,08	-0,08	-0,06	0,09
<b>Perceived Chroma (Clod)</b>	0,04	0,18	0,08	0,22	-0,07	-0,04	-0,07	-0,16	-0,32	0,01
<b>Perceived Hue</b>	-0,08	-0,03	-0,06	-0,25	-0,03	0,07	0,08	-0,09	0,16	0,19
<b>Perceived Value</b>	0,07	0,12	0,05	0,03	0,18	-0,17	-0,01	-0,12	-0,11	0,16
<b>Perceived Chroma</b>	0,01	0,08	0,01	0,22	-0,01	-0,05	0,02	-0,14	-0,34	-0,02
<b>Measured Hue</b>	-0,02	-0,13	-0,04	-0,15	-0,06	0,05	-0,13	-0,07	0,14	0,15
<b>Measured Value</b>	0,12	0,27	0,16	0,12	0,43	-0,40	-0,17	0,03	0,13	0,06
<b>Measured Chroma</b>	0,33	0,37	0,34	0,15	0,36	-0,50	-0,43	0,09	-0,07	-0,13
<b>L*</b>	0,30	0,43	0,34	0,08	0,62	-0,62	-0,36	0,05	0,12	0,06
<b>a*</b>	0,26	0,30	0,26	0,27	0,20	-0,33	-0,26	0,03	-0,28	-0,17
<b>b*</b>	0,38	0,51	0,42	0,15	0,52	-0,62	-0,41	-0,01	-0,10	0,00

**Appendix 3.2.** Spearman-r correlation matrix indicating the relationships between the recorded soil colour variables.

	Hue (perceived, dry)	Value (perceived, dry)	Chroma (Perceived, dry)	Hue (Measured, dry)	Value (Measured, dry)	Chroma (Measured, dry)	L* (dry)	a* (dry)	b* (dry)
Hue (perceived, dry)	1	0,42	-0,52	0,54	0,37	-0,14	0,26	-0,67	-0,01
Value (perceived, dry)		1	-0,05	0,31	0,60	0,08	0,56	-0,15	0,44
Chroma (Perceived, dry)			1	-0,45	-0,12	0,49	0,02	0,78	0,38
Hue (Measured, dry)				1	0,18	-0,20	0,14	-0,50	0,00
Value (Measured, dry)					1	0,38	0,86	-0,03	0,67
Chroma (Measured, dry)						1	0,54	0,65	0,74
L* (dry)							1	0,19	0,86
a* (dry)								1	0,56
b* (dry)									1



**Appendix 3.3.** Spearman-r correlation matrix for the determined soil parameters.

	Co Clay (%)	Fi Clay (%)	Total Clay (%)	Bulk Density (Kg.m-1)	pH (H2O)	pH (KCl)	EC (mS/m)	CBD Fe (%)	AAO Fe (%)	CBD AI (%)	AAO AI (%)
Co Clay (%)	1,00	0,45	0,99	0,02	-0,09	-0,25	0,07	0,74	0,74	0,70	0,65
Fi Clay (%)		1,00	0,57	0,10	0,07	0,14	0,15	0,44	0,17	0,41	0,59
Total Clay (%)			1,00	0,03	-0,09	-0,23	0,09	0,74	0,70	0,70	0,70
Bulk Density (Kg.m-1)				1,00	0,45	0,44	0,30	0,08	-0,11	-0,05	-0,18
pH (Water)					1,00	0,89	0,13	0,01	-0,27	-0,22	-0,30
pH (KCl)						1,00	0,31	-0,11	-0,38	-0,29	-0,27
EC (mS/m)							1,00	0,13	0,00	0,08	0,02
CBD Fe (%)								1,00	0,66	0,78	0,63
AAO Fe (%)									1,00	0,60	0,65
CBD AI (%)										1,00	0,70
AAO AI (%)											1,00
Fe Cl											
AI Ratio (%)											
CBD Fe:Clay											
Coarse Fragments %											
Very CoSa											
CoSa											
MeSa											
FiSa											
Very FiSa											
Total Sand (%)											
CoSi											
FiSi											
Total Silt (%)											
WDC											
SDC											
WDC (%)											
Ca (cmolc.kg-1)											
Mg (cmolc.kg-1)											
Na (cmolc.kg-1)											
K (cmolc.kg-1)											
Exchangeable Basic cations (cmolc.kg-1)											
Al (cmolc.kg-1)											
H (cmolc.kg-1)											
Exchangeable acidity (cmolc.kg- 1)											
ECEC											
ESP											
Ca:Na ratio											
Ca:Mg ratio											
%N											
%C											

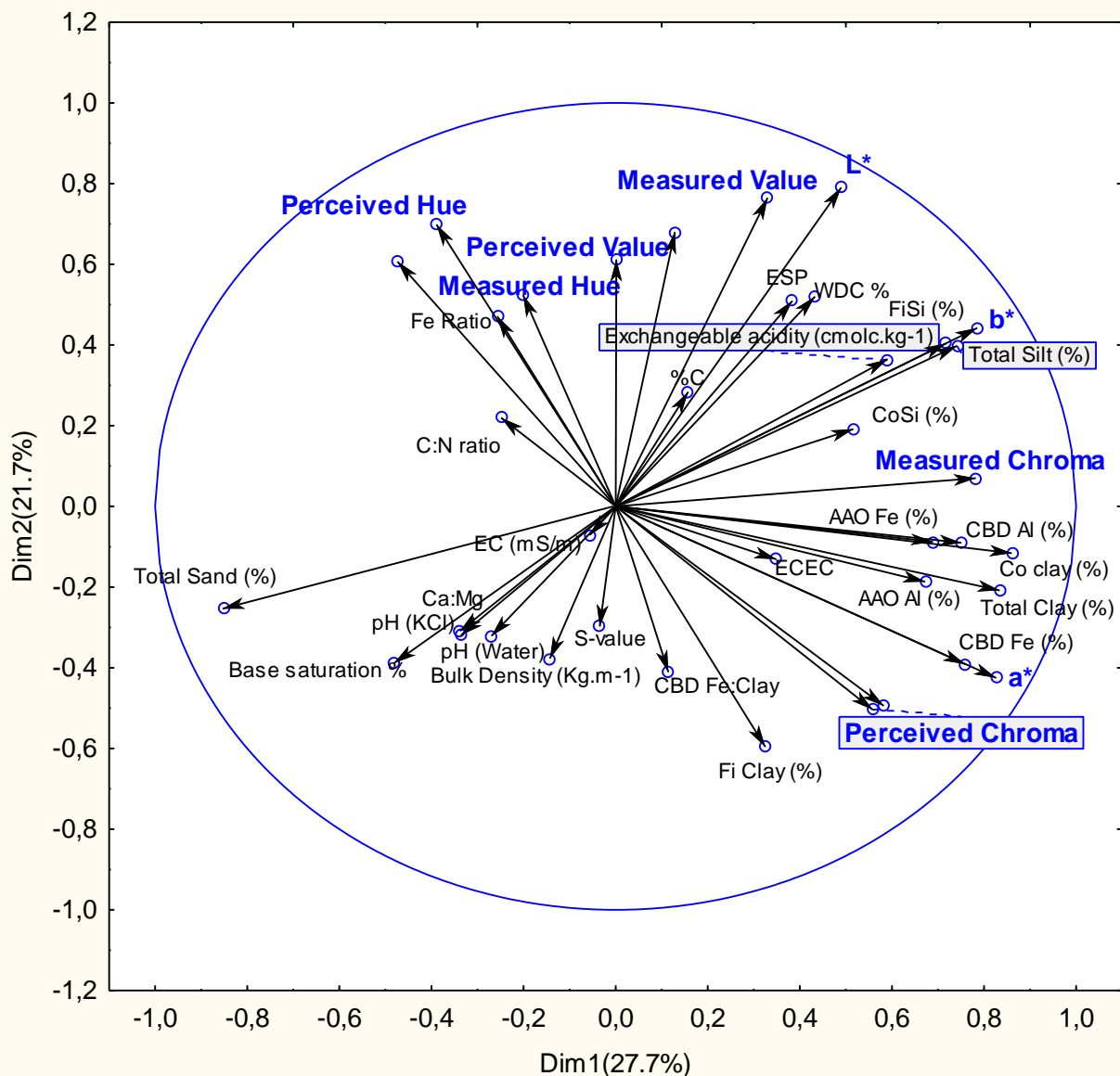
**Appendix 3.3 (Continued).** Spearman-r correlation matrix for the determined soil parameters.

	Fe Cl	Al Ratio (%)	CBD Fe:Clay	Coarse Fragments %	Very CoSa (%)	CoSa (%)	MeSa (%)	FiSa (%)	Very FiSa (%)	Total Sand (%)
Co Clay (%)	-0,29	-0,35	-0,11	0,40	-0,01	-0,56	-0,79	-0,69	0,06	-0,87
Fi Clay (%)	-0,45	-0,11	-0,01	-0,01	0,29	0,01	-0,08	0,10	0,14	-0,11
Total Clay (%)	-0,33	-0,34	-0,13	0,34	0,04	-0,51	-0,73	-0,63	0,07	-0,81
Bulk Density (Kg.m-1)	-0,22	-0,18	0,14	0,24	0,46	0,27	0,14	0,07	-0,24	0,08
pH (Water)	-0,26	-0,06	0,05	0,15	0,36	0,17	0,09	0,19	0,01	0,17
pH (KCl)	-0,28	0,03	0,07	0,09	0,49	0,27	0,28	0,39	0,06	0,31
EC (mS/m)	-0,30	-0,14	-0,02	0,26	0,69	0,18	0,05	0,06	-0,12	-0,04
CBD Fe (%)	-0,62	-0,51	0,51	0,52	0,13	-0,44	-0,62	-0,49	-0,05	-0,65
AAO Fe (%)	0,06	-0,18	0,18	0,49	-0,13	-0,69	-0,78	-0,55	0,24	-0,74
CBD Al (%)	-0,41	-0,73	0,27	0,49	0,01	-0,48	-0,54	-0,36	-0,06	-0,59
AAO Al (%)	-0,26	-0,11	0,13	0,31	-0,05	-0,55	-0,49	-0,25	0,15	-0,56
Fe Ratio (%)	1,00	0,46	-0,42	-0,19	-0,43	-0,13	0,06	0,13	0,36	0,21
Al Ratio (%)		1,00	-0,28	-0,39	-0,18	0,13	0,26	0,24	0,30	0,29
CBD Fe:Clay			1,00	0,35	0,09	-0,04	-0,05	0,01	-0,10	0,00
Coarse Fragments %				1,00	0,31	-0,51	-0,60	-0,26	0,10	-0,43
Very CoSa					1,00	0,35	0,09	0,09	-0,26	0,05
CoSa						1,00	0,81	0,33	-0,51	0,66
MeSa							1,00	0,71	-0,29	0,87
FiSa								1,00	0,26	0,82
Very FiSa									1,00	0,02
Total Sand (%)										1,00
CoSi										
FiSi										
Total Silt (%)										
WDC										
SDC										
WDC (%)										
Ca (cmolc.kg-1)										
Mg (cmolc.kg-1)										
Na (cmolc.kg-1)										
K (cmolc.kg-1)										
Exchangeable Basic cations (cmolc.kg-1)										
Al (cmolc.kg-1)										
H (cmolc.kg-1)										
Exchangeable acidity (cmolc.kg-1)										
ECEC										
ESP										
Ca:Na ratio										
Ca:Mg ratio										
%N										
%C										

**Appendix 3.3 (Continued).** Spearman-r correlation matrix for the determined soil parameters.

	CoSi (%)	FiSi (%)	Total Silt (%)	WDC	SDC	WDC (%)	Ca (cmolc. kg-1)	Mg (cmolc. kg-1)	Na (cmolc. kg-1)	K (cmolc. kg-1)
Co Clay (%)	0,36	0,75	0,74	0,79	0,77	0,39	-0,14	0,41	0,60	0,11
Fi Clay (%)	0,09	-0,08	-0,04	0,10	0,64	-0,37	0,08	0,05	-0,23	-0,08
Total Clay (%)	0,32	0,67	0,66	0,74	0,80	0,30	-0,12	0,39	0,52	0,08
Bulk Density (Kg.m-1)	-0,30	-0,10	-0,17	0,03	0,03	-0,03	0,45	0,00	0,03	0,31
pH (Water)	-0,07	-0,19	-0,19	-0,09	-0,07	-0,07	0,81	0,24	-0,08	0,40
pH (KCl)	-0,03	-0,31	-0,30	-0,27	-0,15	-0,26	0,86	0,24	-0,33	0,34
EC (mS/m)	0,10	-0,01	-0,02	-0,09	0,10	-0,23	0,39	0,01	0,07	0,30
CBD Fe (%)	0,28	0,52	0,54	0,54	0,69	0,17	0,01	0,34	0,39	0,08
AAO Fe (%)	0,41	0,71	0,72	0,63	0,62	0,36	-0,21	0,51	0,40	0,00
CBD Al (%)	0,30	0,45	0,50	0,45	0,62	0,09	-0,24	0,10	0,40	-0,11
AAO Al (%)	0,40	0,41	0,46	0,37	0,74	-0,08	-0,18	0,28	0,06	-0,16
Fe Cl	-0,07	-0,06	-0,08	-0,16	-0,36	0,13	-0,26	-0,02	-0,11	-0,20
Al Ratio (%)	0,02	-0,22	-0,22	-0,28	-0,22	-0,12	0,07	0,08	-0,47	-0,08
CBD Fe:Clay	0,05	0,03	0,06	-0,03	0,04	-0,05	0,11	0,12	-0,07	0,00
Coarse Fragments %	0,15	0,44	0,44	0,36	0,33	0,28	0,25	0,21	0,41	0,22
Very CoSa	-0,05	-0,06	-0,07	0,04	0,17	-0,09	0,40	-0,07	0,08	0,32
CoSa	-0,43	-0,65	-0,69	-0,53	-0,41	-0,37	0,05	-0,46	-0,35	0,08
MeSa	-0,45	-0,87	-0,88	-0,82	-0,57	-0,62	0,08	-0,47	-0,67	-0,17
FiSa	-0,33	-0,84	-0,80	-0,83	-0,34	-0,75	0,30	-0,32	-0,75	-0,33
Very FiSa	0,11	0,04	0,06	-0,07	0,00	-0,06	0,23	0,33	-0,23	-0,08
Total Sand (%)	-0,58	-0,94	-0,95	-0,89	-0,62	-0,60	0,17	-0,45	-0,70	-0,20
CoSi	1,00	0,51	0,65	0,39	0,34	0,17	0,02	0,30	0,20	0,12
FiSi		1,00	0,97	0,89	0,46	0,75	-0,18	0,48	0,73	0,24
Total Silt (%)			1,00	0,87	0,49	0,69	-0,19	0,48	0,70	0,20
WDC				1,00	0,55	0,79	-0,20	0,43	0,73	0,16
SDC					1,00	-0,01	-0,16	0,25	0,34	-0,12
WDC (%)						1,00	-0,16	0,31	0,67	0,25
Ca (cmolc.kg-1)							1,00	0,27	-0,24	0,44
Mg (cmolc.kg-1)								1,00	0,08	0,12
Na (cmolc.kg-1)									1,00	0,21
K (cmolc.kg-1)										1,00
Exchangeable Basic cations (cmolc.kg-1)										
Al (cmolc.kg-1)										
H (cmolc.kg-1)										
Exchangeable acidity (cmolc.kg-1)										
ECEC										
ESP										
Ca:Na ratio										
Ca:Mg ratio										
%N										
%C										

<b>Appendix 3.3 (Continued).</b> Spearman-r correlation matrix for the determined soil parameters.												
	Exchangeable Basic cations (cmolc.kg-1)	Al (cmolc. kg-1)	H (cmolc. kg-1)	Exchangeable acidity (cmolc.kg-1)	ECEC	ESP	Ca:Na ratio	Ca:Mg ratio	%N	%C	C:N ratio	
Co Clay (%)	0,10	0,31	0,40	0,35	0,47	0,30	-0,40	-0,39	0,38	0,09	-0,38	
Fi Clay (%)	0,09	-0,07	0,04	-0,05	-0,01	-0,23	0,17	0,06	-0,08	-0,29	-0,04	
Total Clay (%)	0,10	0,28	0,38	0,32	0,44	0,25	-0,35	-0,36	0,34	0,04	-0,34	
Bulk Density (Kg.m-1)	0,45	-0,48	-0,36	-0,47	0,30	-0,19	0,34	0,44	-0,02	-0,20	-0,22	
pH (Water)	0,80	-0,90	-0,71	-0,89	0,38	-0,37	0,64	0,59	-0,17	-0,27	-0,13	
pH (KCl)	0,78	-0,94	-0,82	-0,95	0,27	-0,57	0,80	0,64	-0,19	-0,25	-0,09	
EC (mS/m)	0,31	-0,20	-0,18	-0,24	0,27	-0,17	0,27	0,42	0,36	0,09	-0,31	
CBD Fe (%)	0,17	0,16	0,30	0,21	0,48	0,05	-0,18	-0,22	0,23	-0,02	-0,28	
AAO Fe (%)	0,05	0,45	0,52	0,48	0,53	0,06	-0,32	-0,48	0,33	0,11	-0,41	
CBD Al (%)	-0,13	0,38	0,49	0,44	0,24	0,24	-0,38	-0,27	0,13	0,01	-0,12	
AAO Al (%)	-0,08	0,39	0,47	0,43	0,28	-0,13	-0,14	-0,35	0,17	0,08	-0,10	
Fe Cl	-0,21	0,23	0,14	0,20	-0,16	0,03	-0,13	-0,19	-0,13	0,00	-0,01	
Al Ratio (%)	0,01	-0,04	-0,17	-0,11	-0,12	-0,38	0,30	0,01	-0,02	0,02	-0,01	
CBD Fe:Clay	0,11	-0,06	0,00	-0,02	0,21	-0,28	0,15	0,00	-0,04	0,04	0,05	
Coarse Fragments %	0,29	-0,06	0,10	-0,03	0,46	0,00	0,03	0,09	0,11	0,05	-0,24	
Very CoSa	0,31	-0,43	-0,28	-0,46	0,15	-0,09	0,32	0,48	0,01	-0,12	-0,06	
CoSa	-0,14	-0,31	-0,31	-0,31	-0,44	-0,04	0,20	0,34	-0,22	-0,18	0,25	
MeSa	-0,17	-0,30	-0,36	-0,32	-0,57	-0,26	0,37	0,39	-0,36	-0,20	0,35	
FiSa	0,07	-0,36	-0,38	-0,39	-0,41	-0,50	0,57	0,53	-0,50	-0,38	0,26	
Very FiSa	0,31	0,00	-0,07	-0,04	0,19	-0,37	0,28	0,04	0,08	0,01	-0,27	
Total Sand (%)	-0,06	-0,35	-0,41	-0,37	-0,54	-0,33	0,46	0,48	-0,44	-0,28	0,32	
CoSi	0,08	0,16	0,11	0,13	0,30	-0,06	-0,09	-0,17	0,18	0,10	-0,15	
FiSi	0,06	0,34	0,37	0,35	0,53	0,36	-0,47	-0,51	0,48	0,42	-0,28	
Total Silt (%)	0,04	0,36	0,36	0,36	0,50	0,33	-0,46	-0,51	0,41	0,36	-0,25	
WDC	0,06	0,26	0,32	0,28	0,46	0,43	-0,48	-0,47	0,32	0,21	-0,20	
SDC	0,01	0,24	0,41	0,29	0,31	0,14	-0,29	-0,27	0,03	-0,24	-0,19	
WDC (%)	0,04	0,18	0,15	0,17	0,35	0,45	-0,41	-0,40	0,34	0,41	-0,11	
Ca (cmolc.kg-1)	0,91	-0,85	-0,71	-0,85	0,50	-0,64	0,87	0,77	0,09	-0,06	-0,27	
Mg (cmolc.kg-1)	0,56	-0,19	-0,14	-0,19	0,62	-0,32	0,19	-0,38	0,21	0,21	-0,25	
Na (cmolc.kg-1)	-0,05	0,31	0,38	0,33	0,35	0,75	-0,66	-0,28	0,36	0,26	-0,18	
K (cmolc.kg-1)	0,47	-0,33	-0,29	-0,33	0,44	-0,15	0,26	0,31	0,42	0,30	-0,40	
Exchangeable Basic cations (cmolc.kg-1)	1,00	-0,78	-0,60	-0,76	0,70	-0,55	0,71	0,51	0,15	-0,03	-0,38	
Al (cmolc.kg-1)		1,00	0,77	0,96	-0,24	0,51	-0,78	-0,64	0,24	0,25	0,04	
H (cmolc.kg-1)			1,00	0,90	-0,04	0,46	-0,71	-0,55	0,16	0,14	0,00	
Exchangeable acidity (cmolc.kg-1)				1,00	-0,20	0,52	-0,80	-0,65	0,22	0,24	0,03	
ECEC					1,00	-0,29	0,25	0,08	0,41	0,20	-0,41	
ESP						1,00	-0,88	-0,41	0,05	0,09	0,16	
Ca:Na ratio							1,00	0,70	-0,07	-0,12	-0,11	
Ca:Mg ratio								1,00	-0,04	-0,22	-0,14	
%N									1,00	0,74	-0,57	
%C										1,00	-0,01	



**Appendix 3.4.** The generated MFA correlation circle representing the relationship between selected soil parameters (black) and soil colour variables (blue).

**Note:** The generated MFA correlation circle provides a visual representation of which soil characteristics are responsible for which colour variations within the sampled soils. The colour variables and soil characteristics were combined into a single data set and the generated dimensions expressed on the axes of Figure 3.4 accounts collectively for 49.4% of the variation in this combined data set. To interpret the figure one must however be familiar with what the arrows and particularly the directions of the arrows represent. If the arrows are of a similar length and run in the same direction it implies a strong positive correlation between the two variables. Where the arrows run in the opposite direction, a negative correlation is implied. Arrows perpendicular to one another suggest no relationship between the represented variables. It is however advised that this figure be inspected together with the above provided correlation matrixes to limit erroneous interpretations.

**Appendix 4.1a** Particle size distributions (%) of the sampled soil profiles.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Co Fragments	Total Sand	Very CoSa	CoSa	MeSa	FiSa	Very FiSa	Total Silt	CoSi	FiSi	Total Clay	Co Clay	Fi Clay
Bp 1.1	MP Highveld	Non bleached	Non bleached	42,3	65,1	12,3	6,8	11,4	20,6	13,9	21,3	7,6	13,7	11,6	1,7	13,3
Bp 1.2	MP Highveld	Non bleached	Non bleached	44,4	56,2	7,9	5,3	9,7	19,9	13,3	25,5	6,9	18,7	15,9	2,4	18,3
Bp 2.1	MP Highveld	Non bleached	Bleached	27,7	73,7	6,6	6,8	16,7	30,3	13,3	16,2	6,7	9,5	8,6	1,5	10,1
Bp 2.2	MP Highveld	Non bleached	Non bleached	29,2	62,8	11,9	5,1	10,3	23,2	12,4	22,0	8,6	13,4	12,6	2,5	15,2
Bp 3.1	MP Highveld	Non bleached	Bleached	15,7	75,3	7,4	9,1	18,5	27,7	12,6	15,9	6,9	9,0	7,7	1,1	8,8
Bp 3.2	MP Highveld	Non bleached	Non bleached	18,4	74,2	8,1	9,2	18,6	27,9	10,4	15,7	6,6	9,1	8,5	1,6	10,1
Bp 3.3	MP Highveld	Non bleached	Non bleached	10,3	59,2	4,7	5,9	12,4	22,7	13,5	24,0	9,7	14,3	13,9	2,8	16,8
Br 1.1	MP Highveld	Non bleached	Non bleached	1,3	76,0	0,1	10,5	33,7	21,6	10,1	16,2	6,2	10,0	6,9	0,9	7,7
Br 1.2	MP Highveld	Non bleached	Non bleached	1,6	77,8	0,2	11,4	35,7	22,4	8,1	14,5	6,0	8,5	6,6	1,1	7,7
Br 2.1	MP Highveld	Bleached	Bleached	2,0	79,8	0,1	10,3	33,6	23,0	12,8	14,2	5,7	8,5	5,3	0,6	5,9
Br 2.2	MP Highveld	Bleached	Bleached	1,8	80,5	0,1	11,9	35,0	23,1	10,4	13,0	4,4	8,6	5,8	0,6	6,4
Br 2.3	MP Highveld	Non bleached	Non bleached	0,8	81,1	0,2	10,8	33,2	25,1	11,8	12,5	4,5	8,0	5,6	0,7	6,3
Hh 1.1	WC	Bleached	Bleached	14,7	39,8	3,0	4,1	6,2	13,1	13,3	48,2	11,9	36,3	12,0	0,0	12,1
Hh 1.2	WC	Non bleached	Bleached	24,2	38,0	4,8	5,3	6,4	10,1	11,4	43,2	7,6	35,6	17,7	1,0	18,8
Hh 2.1	WC	Bleached	Bleached	11,2	25,9	1,3	1,7	3,4	9,2	10,3	59,2	10,2	49,0	14,8	0,1	14,9
Hh 2.2	WC	Non bleached	Bleached	12,6	29,8	1,8	2,7	4,4	9,3	11,6	54,5	11,8	42,8	15,1	0,5	15,6
Hh 3.1	WC	Non bleached	Non bleached	6,5	45,7	7,7	8,2	9,1	9,3	11,3	34,4	4,8	29,6	17,6	2,3	19,9
Hh 3.2	WC	Non bleached	Non bleached	31,8	35,6	5,5	7,5	8,4	8,2	5,9	37,8	8,5	29,3	22,8	3,7	26,5
Hh 4.1	WC	Bleached	Bleached	4,6	34,0	5,1	5,5	6,6	8,2	8,7	47,5	10,0	37,5	17,1	1,4	18,4
Hh 4.2	WC	Non bleached	Non bleached	7,1	34,0	4,8	5,9	7,8	8,9	6,7	44,5	6,0	38,5	20,0	1,5	21,5
Mb 1.1	WC	Bleached	Bleached	3,6	73,4	14,2	19,5	22,0	13,9	3,8	16,4	5,4	11,0	8,9	1,3	10,2
Mb 1.2	WC	Non bleached	Bleached	42,3	65,1	12,3	6,8	11,4	20,6	13,9	21,3	7,6	13,7	11,6	1,7	13,3
Mb 2.1	WC	Non bleached	Non bleached	44,4	56,2	7,9	5,3	9,7	19,9	13,3	25,5	6,9	18,7	15,9	2,4	18,3
Mb 2.2	WC	Non bleached	Non bleached	27,7	73,7	6,6	6,8	16,7	30,3	13,3	16,2	6,7	9,5	8,6	1,5	10,1
Mm 1.1	MP Highveld	Non bleached	Non bleached	29,2	62,8	11,9	5,1	10,3	23,2	12,4	22,0	8,6	13,4	12,6	2,5	15,2
Mm 1.2	MP Highveld	Non bleached	Non bleached	15,7	75,3	7,4	9,1	18,5	27,7	12,6	15,9	6,9	9,0	7,7	1,1	8,8
Mm 2.1	MP Highveld	Non bleached	Non bleached	18,4	74,2	8,1	9,2	18,6	27,9	10,4	15,7	6,6	9,1	8,5	1,6	10,1
Mm 2.2	MP Highveld	Non bleached	Non bleached	10,3	59,2	4,7	5,9	12,4	22,7	13,5	24,0	9,7	14,3	13,9	2,8	16,8
Mm 3.1	MP Highveld	Bleached	Bleached	3,1	67,4	9,0	14,2	15,1	19,6	9,5	18,9	8,0	10,9	11,4	2,3	13,7



**Appendix 4.1a (Continued).** Particle size distributions (%) of the sampled soil profiles.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Co Fragments	Total Sand	Very CoSa	CoSa	MeSa	FiSa	Very FiSa	Total Silt	CoSi	FiSi	Total Clay	Co Clay	Fi Clay
Mm 3.2	MP Highveld	Non bleached	Bleached	3,9	65,7	5,4	10,7	16,0	18,6	15,0	23,3	8,8	14,5	9,9	1,2	11,1
Mm 4.1	MP Highveld	Non bleached	Non bleached	1,8	60,9	5,7	8,3	14,4	19,1	13,4	24,7	9,4	15,3	12,5	1,9	14,4
Mm 4.2	MP Highveld	Non bleached	Non bleached	1,7	72,4	2,8	10,0	19,9	25,2	14,5	15,5	5,7	9,8	10,0	2,0	12,1
Pb 1.1	WC	Non bleached	Bleached	1,8	67,4	3,0	8,2	19,0	24,8	12,3	18,7	8,6	10,1	11,5	2,4	13,9
Pb 1.2	WC	Non bleached	Non bleached	1,4	72,2	2,9	8,2	20,6	26,2	14,1	17,0	8,1	8,9	9,1	1,8	10,9
Pb 2.1	WC	Bleached	Bleached	1,5	64,9	2,9	7,2	17,5	24,8	12,4	19,3	9,1	10,2	12,9	2,9	15,7
Pb 2.2	WC	Non bleached	Bleached	1,7	72,5	3,1	8,1	19,1	26,8	15,3	17,4	8,2	9,2	8,6	1,5	10,1
Pb 3.1	WC	Bleached	Bleached	1,5	65,2	3,0	6,6	16,4	25,2	13,9	19,9	10,0	9,9	12,1	2,8	14,9
Pb 3.2	WC	Non bleached	Bleached	6,8	77,3	3,5	10,2	22,8	28,8	12,1	12,3	4,3	8,0	8,5	1,8	10,4
Rk 1.1	WC	Non bleached	Non bleached	22,7	73,5	8,5	7,1	16,8	29,1	12,1	14,6	6,9	7,8	9,4	2,4	11,8
Rk 1.2	WC	Non bleached	Non bleached	7,1	32,3	1,6	2,0	5,1	11,8	11,8	47,6	17,6	30,0	17,8	2,3	20,1
Rk 2.1	WC	Bleached	Non bleached	4,9	27,6	0,5	1,1	2,9	10,2	12,9	48,4	15,3	33,1	21,0	3,0	24,0
Rk 2.2	WC	Non bleached	Non bleached	4,2	74,7	3,5	4,8	16,8	30,0	19,5	19,6	7,5	12,0	5,6	0,2	5,8
Rk 3.1	WC	Non bleached	Non bleached	4,9	66,4	0,7	2,7	13,1	29,2	20,7	19,8	7,2	12,5	12,0	1,8	13,8
Rk 3.2	WC	Non bleached	Non bleached	9,0	31,5	1,5	1,5	3,7	12,1	12,8	56,5	11,1	45,5	11,9	0,0	11,9
Rk 4.1	WC	Non bleached	Non bleached	6,1	25,0	1,2	1,3	3,2	9,2	10,1	60,0	11,3	48,7	14,5	0,5	15,0
Rk 4.2	WC	Non bleached	Non bleached	10,0	57,5	1,9	1,1	2,9	18,6	33,0	26,3	6,6	19,7	14,9	1,3	16,2
Us 1.1	MP Highveld	Non bleached	Non bleached	5,0	42,2	0,3	0,3	1,6	19,0	21,1	33,3	6,8	26,6	21,6	2,8	24,5
Us 1.2	MP Highveld	Non bleached	Non bleached	19,9	61,8	1,0	1,1	2,3	16,8	40,7	28,2	8,0	20,1	9,8	0,2	10,0
Us 2.1	MP Highveld	Non bleached	Non bleached	13,7	49,2	0,5	0,4	1,9	14,6	31,8	31,7	7,0	24,8	17,5	1,5	19,0
Us 2.2	MP Highveld	Non bleached	Non bleached	14,9	51,7	1,8	1,0	2,5	13,0	33,4	29,2	7,3	21,8	17,5	1,7	19,1
Us 3.1	MP Highveld	Bleached	Bleached	25,7	41,0	0,5	0,7	1,8	10,7	27,3	37,0	12,4	24,6	20,1	1,9	22,0
Us 3.2	MP Highveld	Bleached	Bleached	16,4	43,9	1,6	0,9	2,9	14,7	23,8	37,2	9,6	27,7	17,1	1,7	18,8
W3 1.1	WC	Non bleached	Non bleached	8,1	38,8	2,0	1,4	2,9	12,8	19,7	38,1	8,4	29,7	21,2	1,8	23,1
W3 1.2	WC	Non bleached	Non bleached	3,7	58,6	1,7	5,6	12,8	18,6	19,9	18,0	2,8	15,2	19,6	3,7	23,3

**Appendix 4.2.** The water dispersible clay (WDC) %, sodium dispersible clay (SDC) % and the reported WDC ratio for each of the sampled soil horizons.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	WDC % <sup>1</sup>	SDC %	WDC % <sup>2</sup>
Bp 1.1	MP Highveld	Non bleached	Non bleached	0,200	1,504	13,280
Bp 1.2	MP Highveld	Non bleached	Non bleached	0,574	2,608	22,014
Bp 2.1	MP Highveld	Non bleached	Bleached	0,071	4,190	1,701
Bp 2.2	MP Highveld	Non bleached	Non bleached	0,332	3,035	10,933
Bp 3.1	MP Highveld	Non bleached	Bleached	0,064	0,847	7,567
Bp 3.2	MP Highveld	Non bleached	Non bleached	0,150	1,322	11,349
Bp 3.3	MP Highveld	Non bleached	Non bleached	0,244	3,122	7,825
Br 1.1	MP Highveld	Non bleached	Non bleached	0,056	0,682	8,243
Br 1.2	MP Highveld	Non bleached	Non bleached	0,080	0,787	10,207
Br 2.1	MP Highveld	Bleached	Bleached	0,046	0,427	10,695
Br 2.2	MP Highveld	Bleached	Bleached	0,072	0,480	14,923
Br 2.3	MP Highveld	Non bleached	Non bleached	0,094	0,555	16,873
Hh 1.1	WC	Bleached	Bleached	0,524	1,250	41,930
Hh 1.2	WC	Non bleached	Bleached	1,058	2,087	50,690
Hh 2.1	WC	Bleached	Bleached	0,618	1,387	44,542
Hh 2.2	WC	Non bleached	Bleached	1,002	1,747	57,354
Hh 3.1	WC	Non bleached	Non bleached	0,874	2,483	35,210
Hh 3.2	WC	Non bleached	Non bleached	0,601	4,001	15,015
Hh 4.1	WC	Bleached	Bleached	1,362	2,273	59,906
Hh 4.2	WC	Non bleached	Non bleached	0,794	2,834	28,014
Mb 1.1	WC	Bleached	Bleached	0,255	0,999	25,478
Mb 1.2	WC	Non bleached	Bleached	0,311	2,433	12,767
Mb 2.1	WC	Non bleached	Non bleached	0,190	0,897	21,200
Mb 2.2	WC	Non bleached	Non bleached	0,312	1,955	15,959
Mm 1.1	MP Highveld	Non bleached	Non bleached	0,106	1,472	7,179
Mm 1.2	MP Highveld	Non bleached	Non bleached	0,164	1,866	8,805
Mm 2.1	MP Highveld	Non bleached	Non bleached	0,128	1,139	11,208
Mm 2.2	MP Highveld	Non bleached	Non bleached	0,274	2,968	9,228
Mm 3.1	MP Highveld	Bleached	Bleached	0,131	1,163	11,218
Mm 3.2	MP Highveld	Non bleached	Bleached	0,211	2,642	8,004
Mm 4.1	MP Highveld	Non bleached	Non bleached	0,132	1,255	10,489
Mm 4.2	MP Highveld	Non bleached	Non bleached	0,054	1,312	4,103
Pb 1.1	WC	Non bleached	Bleached	0,671	2,309	29,047
Pb 1.2	WC	Non bleached	Non bleached	0,657	3,748	17,514
Pb 2.1	WC	Bleached	Bleached	0,085	0,552	15,475
Pb 2.2	WC	Non bleached	Bleached	0,177	2,071	8,528
Pb 3.1	WC	Bleached	Bleached	0,727	1,455	49,930
Pb 3.2	WC	Non bleached	Bleached	0,661	3,101	21,316
Rk 1.1	WC	Non bleached	Non bleached	0,612	1,821	33,616
Rk 1.2	WC	Non bleached	Non bleached	1,504	4,956	30,354
Rk 2.1	WC	Bleached	Non bleached	0,294	1,009	29,098
Rk 2.2	WC	Non bleached	Non bleached	0,745	2,952	25,236
Rk 3.1	WC	Non bleached	Non bleached	0,263	1,603	16,430
Rk 3.2	WC	Non bleached	Non bleached	0,559	2,833	19,725
Rk 4.1	WC	Non bleached	Non bleached	0,390	1,713	22,761
Rk 4.2	WC	Non bleached	Non bleached	0,592	2,755	21,479
Us 1.1	MP Highveld	Non bleached	Non bleached	0,263	2,066	12,745
Us 1.2	MP Highveld	Non bleached	Non bleached	0,246	2,949	8,357
Us 2.1	MP Highveld	Non bleached	Non bleached	0,114	1,313	8,691

**Appendix 4.2 (Continued).** The water dispersible clay (WDC) %, sodium dispersible clay (SDC) % and reported WDC ratio for each of the sampled soil horizons.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	WDC % <sup>1</sup>	SDC %	WDC % <sup>2</sup>
Us 2.2	MP Highveld	Non bleached	Non bleached	0,074	2,636	2,825
Us 3.1	MP Highveld	Bleached	Bleached	0,090	1,001	9,026
Us 3.2	MP Highveld	Bleached	Bleached	0,177	2,031	8,702
W3 1.1	WC	Non bleached	Non bleached	0,298	2,439	12,224
W3 1.2	WC	Non bleached	Non bleached	0,205	10,074	2,036

<sup>1</sup> Water dispersible clay determined as a percentage of the total clay fraction

<sup>2</sup> Reported WDC (%): (WDC % of total clay fraction / SDC % of the total clay fraction ) \* 100

**Appendix 4.3.** Changes in the different clay fractions from the first to the second horizon of the sampled soil profiles.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Fi clay change % <sup>1</sup>	Co clay change % <sup>1</sup>	Total clay change % <sup>1</sup>
Bp 1	MP Highveld	Non bleached	Non bleached	34,83	37,79	37,40
Bp 2	MP Highveld	Non bleached	Bleached	66,99	47,13	50,13
Bp 3	MP Highveld	Non bleached	Bleached	41,06	10,71	14,64
Br 1	MP Highveld	Non bleached	Non bleached	25,77	-3,27	-0,05
Br 2	MP Highveld	Bleached	Bleached	5,03	8,78	8,41
Hh 1	WC	Non bleached	Bleached	3901,63	47,32	55,65
Hh 2	WC	Bleached	Bleached	641,79	2,09	5,01
Hh 3	WC	Non bleached	Non bleached	59,86	29,81	33,32
Hh 4	WC	Bleached	Bleached	9,42	17,01	16,45
Mb 1	WC	Bleached	Bleached	75,11	28,43	34,56
Mb 2	WC	Non bleached	Non bleached	62,27	26,40	30,13
Mm 1	MP Highveld	Non bleached	Non bleached	19,06	14,37	15,16
Mm 2	MP Highveld	Non bleached	Non bleached	58,20	41,66	44,41
Mm 3	MP Highveld	Bleached	Bleached	82,99	40,80	47,14
Mm 4	MP Highveld	Non bleached	Non bleached	30,52	10,49	13,99
Pb 1	WC	Non bleached	Bleached	33,83	17,82	19,62
Pb 2	WC	Bleached	Bleached	943,03	114,75	139,86
Pb 3	WC	Bleached	Bleached	1183,99	22,14	25,89
Rk 1	WC	Non bleached	Non bleached	114,37	45,47	51,11
Rk 2	WC	Non bleached	Non bleached	511,10	78,51	89,04
Rk 3	WC	Non bleached	Non bleached	15,41	14,91	14,95
Rk 4	WC	Non bleached	Non bleached	9,13	24,11	22,77
Us 1	MP Highveld	Non bleached	Non bleached	-27,86	-26,75	-26,92
Us 2	MP Highveld	Non bleached	Non bleached	31,54	24,39	25,35
Us 3	MP Highveld	Bleached	Bleached	41,34	21,31	23,74
W3	WC	Bleached	Non bleached	-	-	87,68

<sup>1</sup> Clay change %: [(Clay % horizon 2 – Clay % horizon 1) / Clay % horizon 1] \* 100

**Appendix 4.4.** The pH (KCl and water) and electrical conductivity (EC) (mS/m) measured in a 1:2.5 soil solution of the sampled soil horizons. The measured pH in 1M NaF (1:50 soil solution) is also included.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	pH (H <sub>2</sub> O)	pH (KCl)	pH (NaF)	EC (mS/m)
Bp 1.1	MP Highveld	Non bleached	Non bleached	6,25	5,32	9,02	10,90
Bp 1.2	MP Highveld	Non bleached	Non bleached	6,15	5,13	9,20	6,47
Bp 2.1	MP Highveld	Non bleached	Bleached	6,43	5,61	8,51	12,93
Bp 2.2	MP Highveld	Non bleached	Non bleached	5,61	4,66	9,19	9,29
Bp 3.1	MP Highveld	Non bleached	Bleached	6,99	6,23	8,57	13,24
Bp 3.2	MP Highveld	Non bleached	Non bleached	7,24	6,28	8,77	7,77
Bp 3.3	MP Highveld	Non bleached	Non bleached	6,16	5,19	9,22	14,58
Br 1.1	MP Highveld	Non bleached	Non bleached	5,66	4,44	7,88	1,491
Br 1.2	MP Highveld	Non bleached	Non bleached	5,37	4,25	8,09	1,086
Br 2.1	MP Highveld	Bleached	Bleached	5,5	4,22	7,63	1,28
Br 2.2	MP Highveld	Bleached	Bleached	5,32	4,23	7,63	1,139
Br 2.3	MP Highveld	Non bleached	Non bleached	5,37	4,23	7,65	0,974
Hh 1.1	WC	Bleached	Bleached	5,95	4,91	7,75	11,83
Hh 1.2	WC	Non bleached	Bleached	5,94	4,73	8,53	1,698
Hh 2.1	WC	Bleached	Bleached	6,17	5,06	7,97	7,26
Hh 2.2	WC	Non bleached	Bleached	6,17	4,88	8,22	1,613
Hh 3.1	WC	Non bleached	Non bleached	5,03	3,98	8,59	10,14
Hh 3.2	WC	Non bleached	Non bleached	5,05	4,06	9,41	6,95
Hh 4.1	WC	Bleached	Bleached	4,81	3,82	8,41	15,7
Hh 4.2	WC	Non bleached	Non bleached	4,99	3,86	8,96	8,28
Mb 1.1	WC	Bleached	Bleached	6,07	5,22	7,79	12,32
Mb 1.2	WC	Non bleached	Bleached	5,72	4,45	8,46	6,48
Mb 2.1	WC	Non bleached	Non bleached	5,77	5,01	7,76	17,43
Mb 2.2	WC	Non bleached	Non bleached	6,45	5,46	8,03	11,11
Mm 1.1	MP Highveld	Non bleached	Non bleached	5,41	4,43	8,58	7,21
Mm 1.2	MP Highveld	Non bleached	Non bleached	5,11	4,25	9,00	7,51
Mm 2.1	MP Highveld	Non bleached	Non bleached	5,62	4,60	8,65	7,56
Mm 2.2	MP Highveld	Non bleached	Non bleached	6,44	5,32	9,18	1,424
Mm 3.1	MP Highveld	Bleached	Bleached	5,83	4,78	8,67	6,39
Mm 3.2	MP Highveld	Non bleached	Bleached	6,65	5,63	9,28	5,95
Mm 4.1	MP Highveld	Non bleached	Non bleached	5,12	4,32	8,58	15,42
Mm 4.2	MP Highveld	Non bleached	Non bleached	6,40	5,59	8,99	14,73
Pb 1.1	WC	Non bleached	Bleached	5,33	4,17	9,57	1,673
Pb 1.2	WC	Non bleached	Non bleached	5,28	4,18	9,69	1,587
Pb 2.1	WC	Bleached	Bleached	5,33	4,18	7,79	5,65
Pb 2.2	WC	Non bleached	Bleached	4,81	4,25	9,06	1,589
Pb 3.1	WC	Bleached	Bleached	4,97	3,97	8,74	5,81
Pb 3.2	WC	Non bleached	Bleached	4,72	3,79	9,14	6,45
Rk 1.1	WC	Non bleached	Non bleached	5,71	4,45	7,75	6,42
Rk 1.2	WC	Non bleached	Non bleached	6,05	4,43	8,51	1,159
Rk 2.1	WC	Bleached	Non bleached	5,04	3,80	7,71	1,574
Rk 2.2	WC	Non bleached	Non bleached	5,55	4,02	8,74	1,214
Rk 3.1	WC	Non bleached	Non bleached	5,60	4,40	8,70	7,71
Rk 3.2	WC	Non bleached	Non bleached	5,28	4,04	9,48	1,286
Rk 4.1	WC	Non bleached	Non bleached	5,78	4,80	8,52	16,39
Rk 4.2	WC	Non bleached	Non bleached	5,80	4,33	9,09	1,648
Us 1.1	MP Highveld	Non bleached	Non bleached	5,77	4,71	9,18	7,55
Us 1.2	MP Highveld	Non bleached	Non bleached	5,02	4,32	9,49	11,67
Us 2.1	MP Highveld	Non bleached	Non bleached	5,27	4,47	8,58	12,15

**Appendix 4.4 (continued).** The pH (KCl and water) and electrical conductivity (EC) (mS/m) measured in a 1:2.5 so solution for each of the sampled soil horizons. The measured pH in 1M NaF (1:50 soil solution) is also included.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	pH (H <sub>2</sub> O)	pH (KCl)	pH (NaF)	EC (mS/m)
Us 2.2	MP Highveld	Non bleached	Non bleached	4,86	4,22	9,01	11,27
Us 3.1	MP Highveld	Bleached	Bleached	5,56	4,52	8,39	1,711
Us 3.2	MP Highveld	Bleached	Bleached	5,01	4,27	8,98	9,70
W3 1.1	WC	Non bleached	Non bleached	5,83	4,33	8,33	19,07
W3 1.2	WC	Non bleached	Non bleached	5,40	4,16	9,17	44,10



**Appendix 4.5.** Exchangeable cations and calculated cation parameters for each of the sampled soil horizons.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Ca (cmol <sub>c</sub> .kg <sup>-1</sup> )	Mg (cmol <sub>c</sub> .kg <sup>-1</sup> )	Na (cmol <sub>c</sub> .kg <sup>-1</sup> )	K (cmol <sub>c</sub> .kg <sup>-1</sup> )	S-value (cmol <sub>c</sub> .kg <sup>-1</sup> )	Exchangeable Al (cmol <sub>c</sub> .kg <sup>-1</sup> )	Exchangeable Acidity (cmol <sub>c</sub> .kg <sup>-1</sup> )	ECEC	Base saturation %	ESP	Ca:Mg
Bp 1.1	MP Highveld	Non bleached	Non bleached	2,69	0,63	0,07	0,38	3,77	0,00	0,04	3,82	98,91	1,82	4,25
Bp 1.2	MP Highveld	Non bleached	Non bleached	2,40	0,58	0,07	0,20	3,26	0,05	0,04	3,30	98,74	2,24	4,11
Bp 2.1	MP Highveld	Non bleached	Bleached	2,38	0,53	0,07	0,33	3,30	0,05	0,09	3,39	97,30	1,92	4,44
Bp 2.2	MP Highveld	Non bleached	Non bleached	1,61	0,48	0,08	0,14	2,30	0,10	0,14	2,44	94,20	3,21	3,37
Bp 3.1	MP Highveld	Non bleached	Bleached	2,95	0,72	0,07	0,44	4,18	0,00	0,02	4,19	99,60	1,56	4,07
Bp 3.2	MP Highveld	Non bleached	Non bleached	2,36	0,69	0,06	0,22	3,33	0,00	0,02	3,34	99,50	1,69	3,41
Bp 3.3	MP Highveld	Non bleached	Non bleached	1,95	0,67	0,07	0,16	2,83	0,03	0,07	2,90	97,70	2,25	2,92
Br 1.1	MP Highveld	Non bleached	Non bleached	0,88	0,49	0,06	0,26	1,68	0,25	0,24	1,92	87,40	2,95	1,81
Br 1.2	MP Highveld	Non bleached	Non bleached	0,40	0,52	0,06	0,13	1,11	0,40	0,44	1,55	71,48	3,65	0,78
Br 2.1	MP Highveld	Bleached	Bleached	0,70	0,47	0,06	0,19	1,42	0,25	0,34	1,76	80,64	3,45	1,49
Br 2.2	MP Highveld	Bleached	Bleached	0,57	0,39	0,05	0,10	1,12	0,25	0,39	1,51	74,06	3,46	1,44
Br 2.3	MP Highveld	Non bleached	Non bleached	0,54	0,43	0,06	0,09	1,12	0,25	0,34	1,46	76,63	3,87	1,27
Hh 1.1	WC	Bleached	Bleached	1,35	1,09	0,17	0,40	3,00	0,05	0,04	3,04	98,63	5,43	1,24
Hh 1.2	WC	Non bleached	Bleached	0,95	1,05	0,12	0,43	2,55	0,05	0,14	2,69	94,73	4,37	0,91
Hh 2.1	WC	Bleached	Bleached	2,80	1,72	0,11	0,42	5,05	0,02	0,04	5,09	99,18	2,13	1,63
Hh 2.2	WC	Non bleached	Bleached	2,73	1,23	0,16	0,24	4,36	0,02	0,04	4,40	99,05	3,56	2,23
Hh 3.1	WC	Non bleached	Non bleached	0,17	0,63	0,17	0,37	1,34	0,98	1,44	2,78	48,23	6,09	0,28
Hh 3.2	WC	Non bleached	Non bleached	0,07	0,54	0,13	0,32	1,07	1,00	1,34	2,41	44,33	5,41	0,13
Hh 4.1	WC	Bleached	Bleached	0,42	0,79	0,30	0,15	1,65	1,40	1,84	3,49	47,27	8,47	0,53
Hh 4.2	WC	Non bleached	Non bleached	0,24	0,68	0,23	0,09	1,25	1,30	1,74	2,99	41,75	7,56	0,36
Mb 1.1	WC	Bleached	Bleached	1,57	0,44	0,10	0,34	2,44	0,00	0,02	2,46	99,32	4,07	3,60
Mb 1.2	WC	Non bleached	Bleached	0,89	0,34	0,10	0,36	1,68	0,13	0,17	1,85	90,97	5,18	2,63
Mb 2.1	WC	Non bleached	Non bleached	1,98	0,61	0,11	0,39	3,08	0,10	0,09	3,17	97,11	3,43	3,25
Mb 2.2	WC	Non bleached	Non bleached	1,77	0,69	0,07	0,40	2,93	0,05	0,02	2,95	99,44	2,51	2,56
Mm 1.1	MP Highveld	Non bleached	Non bleached	1,48	0,48	0,07	0,26	2,28	0,08	0,19	2,47	92,25	2,64	3,09
Mm 1.2	MP Highveld	Non bleached	Non bleached	1,19	0,45	0,05	0,19	1,89	0,28	0,31	2,20	85,82	2,37	2,64
Mm 2.1	MP Highveld	Non bleached	Non bleached	1,50	0,51	0,06	0,36	2,43	0,13	0,12	2,55	95,24	2,21	2,94
Mm 2.2	MP Highveld	Non bleached	Non bleached	1,71	0,68	0,06	0,15	2,59	0,00	0,04	2,64	98,42	2,14	2,50
Mm 3.1	MP Highveld	Bleached	Bleached	1,97	0,56	0,05	0,35	2,94	0,08	0,04	2,98	98,60	1,75	3,52

**Appendix 4.5 (continued).** Exchangeable cations and calculated cation parameters for each of the sampled soil horizons.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Ca (cmol <sub>c</sub> .kg <sup>-1</sup> )	Mg (cmol <sub>c</sub> .kg <sup>-1</sup> )	Na (cmol <sub>c</sub> .kg <sup>-1</sup> )	K (cmol <sub>c</sub> .kg <sup>-1</sup> )	S-value (cmol <sub>c</sub> .kg <sup>-1</sup> )	Exchangeable Al (cmol <sub>c</sub> .kg <sup>-1</sup> )	Exchangeable Acidity (cmol <sub>c</sub> .kg <sup>-1</sup> )	ECEC	Base saturation %	ESP	Ca:Mg
Mm 3.2	MP Highveld	Non bleached	Bleached	1,79	0,83	0,05	0,18	2,84	0,00	0,02	2,87	99,24	1,67	2,15
Mm 4.1	MP Highveld	Non bleached	Non bleached	1,56	0,28	0,05	0,27	2,16	0,20	0,24	2,40	90,14	2,18	5,57
Mm 4.2	MP Highveld	Non bleached	Non bleached	2,02	0,13	0,06	0,16	2,37	0,00	0,02	2,38	99,30	2,37	15,35
Pb 1.1	WC	Non bleached	Bleached	0,69	0,49	0,12	0,31	1,61	0,90	1,24	2,86	56,52	4,11	1,40
Pb 1.2	WC	Non bleached	Non bleached	0,60	0,67	0,10	0,26	1,64	0,75	0,94	2,58	63,54	4,04	0,89
Pb 2.1	WC	Bleached	Bleached	1,05	0,33	0,10	0,12	1,61	0,35	0,59	2,20	73,12	4,74	3,20
Pb 2.2	WC	Non bleached	Bleached	0,10	0,08	0,08	0,07	0,33	0,95	1,14	1,48	22,66	5,30	1,27
Pb 3.1	WC	Bleached	Bleached	0,37	0,37	0,10	0,28	1,13	1,40	1,79	2,92	38,74	3,57	1,01
Pb 3.2	WC	Non bleached	Bleached	0,12	0,63	0,11	0,23	1,09	1,60	2,09	3,18	34,25	3,42	0,19
Rk 1.1	WC	Non bleached	Non bleached	1,09	0,87	0,10	0,13	2,19	0,30	0,14	2,33	93,92	4,48	1,25
Rk 1.2	WC	Non bleached	Non bleached	1,11	2,71	0,15	0,07	4,04	0,10	0,24	4,28	94,35	3,56	0,41
Rk 2.1	WC	Bleached	Non bleached	0,93	0,50	0,08	0,23	1,75	0,50	0,84	2,59	67,50	3,19	1,86
Rk 2.2	WC	Non bleached	Non bleached	0,60	1,52	0,13	0,07	2,33	0,50	0,74	3,07	75,83	4,11	0,40
Rk 3.1	WC	Non bleached	Non bleached	1,85	0,92	0,10	0,49	3,36	0,20	0,34	3,70	90,77	2,70	2,01
Rk 3.2	WC	Non bleached	Non bleached	0,85	0,53	0,10	0,22	1,70	1,40	1,84	3,54	48,05	2,82	1,59
Rk 4.1	WC	Non bleached	Non bleached	3,50	1,32	0,09	0,94	5,85	0,10	0,09	5,94	98,46	1,46	2,64
Rk 4.2	WC	Non bleached	Non bleached	1,39	0,81	0,09	0,69	2,99	0,35	0,49	3,48	85,88	2,62	1,71
Us 1.1	MP Highveld	Non bleached	Non bleached	1,99	1,32	0,05	0,34	3,70	0,07	0,12	3,82	96,94	1,25	1,50
Us 1.2	MP Highveld	Non bleached	Non bleached	0,73	1,30	0,06	0,14	2,23	0,50	0,67	2,89	76,95	1,95	0,56
Us 2.1	MP Highveld	Non bleached	Non bleached	1,31	0,81	0,04	0,13	2,28	0,25	0,34	2,62	86,98	1,66	1,62
Us 2.2	MP Highveld	Non bleached	Non bleached	0,64	0,69	0,05	0,07	1,45	0,65	0,79	2,24	64,72	2,13	0,92
Us 3.1	MP Highveld	Bleached	Bleached	1,60	0,72	0,05	0,14	2,51	0,15	0,19	2,71	92,92	1,93	2,21
Us 3.2	MP Highveld	Bleached	Bleached	0,81	0,85	0,05	0,08	1,79	0,43	0,64	2,43	73,58	2,15	0,95
W3 1.1	WC	Non bleached	Non bleached	1,24	0,30	0,28	0,24	2,05	0,30	0,62	2,66	76,85	10,45	4,18
W3 1.2	WC	Non bleached	Non bleached	1,02	0,35	0,70	0,20	2,27	0,55	0,89	3,16	71,82	22,27	2,96

**Appendix 4.6.** The extracted citrate-bicarbonate-dithionite (CBD) and acidified ammonium oxalate (AAO) Fe and Al fractions from the sampled soil profiles.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Fe <sub>CBD</sub> (%)	Fe <sub>AAO</sub> (%)	Fe Cl <sup>1</sup>	Al <sub>CBD</sub> (%)	Al <sub>AAO</sub> (%)	Al ratio <sup>2</sup>
Bp 1.1	MP Highveld	Non bleached	Non bleached	2,39	0,13	5,27	0,34	0,14	41,07
Bp 1.2	MP Highveld	Non bleached	Non bleached	3,24	0,12	3,71	0,40	0,15	37,88
Bp 2.1	MP Highveld	Non bleached	Bleached	1,88	0,11	5,76	0,14	0,13	91,67
Bp 2.2	MP Highveld	Non bleached	Non bleached	2,02	0,11	5,66	0,35	0,17	49,15
Bp 3.1	MP Highveld	Non bleached	Bleached	1,35	0,11	8,00	0,23	0,11	46,15
Bp 3.2	MP Highveld	Non bleached	Non bleached	1,47	0,10	6,55	0,26	0,12	46,51
Bp 3.3	MP Highveld	Non bleached	Non bleached	1,88	0,10	5,44	0,37	0,17	45,90
Br 1.1	MP Highveld	Non bleached	Non bleached	1,29	0,09	6,98	0,22	0,10	47,22
Br 1.2	MP Highveld	Non bleached	Non bleached	1,67	0,08	5,03	0,27	0,10	37,78
Br 2.1	MP Highveld	Bleached	Bleached	0,67	0,07	10,83	0,11	0,09	78,95
Br 2.2	MP Highveld	Bleached	Bleached	0,61	0,07	11,80	0,11	0,08	73,68
Br 2.3	MP Highveld	Non bleached	Non bleached	0,61	0,10	15,74	0,11	0,10	88,89
Hh 1.1	WC	Bleached	Bleached	1,06	0,10	9,06	0,17	0,08	48,28
Hh 1.2	WC	Non bleached	Bleached	2,06	0,14	6,99	0,37	0,11	31,15
Hh 2.1	WC	Bleached	Bleached	2,17	0,11	4,98	0,23	0,13	53,85
Hh 2.2	WC	Non bleached	Bleached	2,54	0,11	4,26	0,26	0,12	46,51
Hh 3.1	WC	Non bleached	Non bleached	2,55	0,11	4,47	0,38	0,16	41,27
Hh 3.2	WC	Non bleached	Non bleached	3,70	0,13	3,57	0,51	0,22	42,35
Hh 4.1	WC	Bleached	Bleached	2,78	0,14	4,96	0,40	0,14	34,33
Hh 4.2	WC	Non bleached	Non bleached	1,31	0,15	11,49	0,26	0,16	62,79
Mb 1.1	WC	Bleached	Bleached	0,90	0,08	8,67	0,15	0,07	48,00
Mb 1.2	WC	Non bleached	Bleached	1,24	0,08	6,80	0,21	0,10	45,71
Mb 2.1	WC	Non bleached	Non bleached	1,16	0,09	7,76	0,10	0,07	70,59
Mb 2.2	WC	Non bleached	Non bleached	1,50	0,11	7,22	0,10	0,09	93,75
Mm 1.1	MP Highveld	Non bleached	Non bleached	1,57	0,08	5,37	0,23	0,10	43,59
Mm 1.2	MP Highveld	Non bleached	Non bleached	1,56	0,11	6,92	0,13	0,13	95,45
Mm 2.1	MP Highveld	Non bleached	Non bleached	1,05	0,08	7,43	0,16	0,10	62,96
Mm 2.2	MP Highveld	Non bleached	Non bleached	1,44	0,10	6,69	0,19	0,17	90,32
Mm 3.1	MP Highveld	Bleached	Bleached	1,12	0,08	7,53	0,17	0,12	68,97
Mm 3.2	MP Highveld	Non bleached	Bleached	1,44	0,09	6,27	0,24	0,15	62,50
Mm 4.1	MP Highveld	Non bleached	Non bleached	1,17	0,08	6,67	0,23	0,11	50,00
Mm 4.2	MP Highveld	Non bleached	Non bleached	3,13	0,08	2,50	0,46	0,13	27,63
Pb 1.1	WC	Non bleached	Bleached	2,28	0,14	6,07	0,61	0,27	44,12
Pb 1.2	WC	Non bleached	Non bleached	2,45	0,14	5,89	0,59	0,28	46,94
Pb 2.1	WC	Bleached	Bleached	0,56	0,08	15,14	0,18	0,11	60,00
Pb 2.2	WC	Non bleached	Bleached	1,08	0,08	7,81	0,38	0,16	41,27
Pb 3.1	WC	Bleached	Bleached	1,56	0,15	9,65	0,30	0,15	50,00
Pb 3.2	WC	Non bleached	Bleached	2,33	0,19	7,98	0,40	0,19	46,97
Rk 1.1	WC	Non bleached	Non bleached	1,65	0,11	6,57	0,25	0,12	48,78
Rk 1.2	WC	Non bleached	Non bleached	4,58	0,35	7,61	0,53	0,14	27,27
Rk 2.1	WC	Bleached	Non bleached	1,21	0,12	9,92	0,15	0,10	64,00
Rk 2.2	WC	Non bleached	Non bleached	2,07	0,26	12,75	0,25	0,14	58,54
Rk 3.1	WC	Non bleached	Non bleached	1,99	0,15	7,54	0,32	0,16	48,15
Rk 3.2	WC	Non bleached	Non bleached	2,46	0,26	10,73	0,47	0,24	50,63
Rk 4.1	WC	Non bleached	Non bleached	1,90	0,17	9,18	0,32	0,15	47,17
Rk 4.2	WC	Non bleached	Non bleached	2,73	0,19	7,05	0,41	0,19	47,06
Us 1.1	MP Highveld	Non bleached	Non bleached	1,70	0,11	6,71	0,20	0,21	102,94
Us 1.2	MP Highveld	Non bleached	Non bleached	2,87	0,14	5,02	0,33	0,25	74,55
Us 2.1	MP Highveld	Non bleached	Non bleached	1,49	0,11	7,27	0,29	0,16	55,10

**Appendix 4.6 (continued).** The extracted citrate-bicarbonate-dithionite (CBD) and acidified ammonium oxalate (AAO) Fe and Al fractions from the sampled soil profiles.

Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	Fe <sub>CBD</sub> (%)	Fe <sub>AAO</sub> (%)	Fe Cl <sup>1</sup>	Al <sub>CBD</sub> (%)	Al <sub>AAO</sub> (%)	Al ratio <sup>2</sup>
Us 2.2	MP Highveld	Non bleached	Non bleached	1,73	0,16	9,39	0,34	0,19	54,39
Us 3.1	MP Highveld	Bleached	Bleached	1,13	0,11	9,56	0,25	0,12	48,78
Us 3.2	MP Highveld	Bleached	Bleached	1,50	0,16	10,43	0,32	0,16	49,06
W3 1.1	WC	Non bleached	Non bleached	1,68	0,11	6,79	0,41	0,10	24,64
W3 1.2	WC	Non bleached	Non bleached	3,03	0,13	4,16	0,72	0,16	22,50

<sup>1</sup> Fe Cl:  $[\text{Fe}_{\text{AAO}} (\text{mg} \cdot \text{kg}^{-1}) / \text{Fe}_{\text{CBD}} (\text{mg} \cdot \text{kg}^{-1})] * 100$

<sup>2</sup> Al ratio:  $[\text{Al}_{\text{AAO}} (\text{mg} \cdot \text{kg}^{-1}) / \text{Al}_{\text{CBD}} (\text{mg} \cdot \text{kg}^{-1})] * 100$

**Appendix 4.7.** The organic carbon and nitrogen percentages of each of the sampled soil horizons and their calculated C:N ratio.

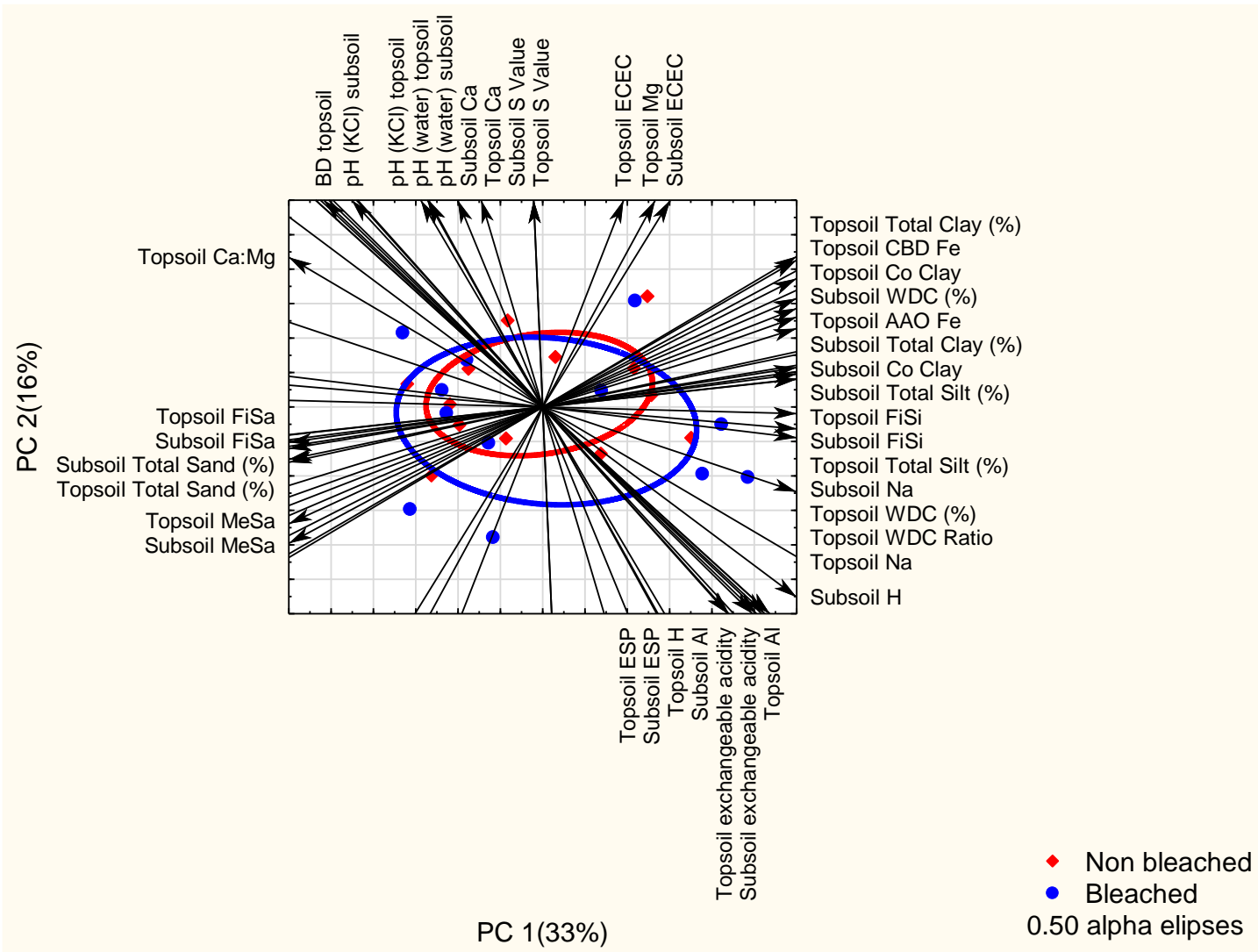
Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	C %	N %	C:N
Bp 1.1	MP Highveld	Non bleached	Non bleached	0,933	0,052	17,94
Bp 1.2	MP Highveld	Non bleached	Non bleached	0,905	0,049	18,47
Bp 2.1	MP Highveld	Non bleached	Bleached	0,760	0,047	16,17
Bp 2.2	MP Highveld	Non bleached	Non bleached	0,753	0,038	19,82
Bp 3.1	MP Highveld	Non bleached	Bleached	0,743	0,044	16,89
Bp 3.2	MP Highveld	Non bleached	Non bleached	0,771	0,021	36,71
Bp 3.3	MP Highveld	Non bleached	Non bleached	0,669	0,032	20,91
Br 1.1	MP Highveld	Non bleached	Non bleached	1,367	0,056	24,41
Br 1.2	MP Highveld	Non bleached	Non bleached	0,896	0,019	47,16
Br 2.1	MP Highveld	Bleached	Bleached	1,109	0,045	24,64
Br 2.2	MP Highveld	Bleached	Bleached	0,722	0,023	31,39
Br 2.3	MP Highveld	Non bleached	Non bleached	0,635	0,009	70,56
Hh 1.1	WC	Bleached	Bleached	1,570	0,048	32,71
Hh 1.2	WC	Non bleached	Bleached	0,642	0,000	0,00
Hh 2.1	WC	Bleached	Bleached	1,523	0,086	17,71
Hh 2.2	WC	Non bleached	Bleached	1,062	0,051	20,82
Hh 3.1	WC	Non bleached	Non bleached	1,854	0,075	24,72
Hh 3.2	WC	Non bleached	Non bleached	1,219	0,065	18,75
Hh 4.1	WC	Bleached	Bleached	2,361	0,093	25,39
Hh 4.2	WC	Non bleached	Non bleached	1,338	0,061	21,93
Mb 1.1	WC	Bleached	Bleached	0,973	0,088	11,06
Mb 1.2	WC	Non bleached	Bleached	0,635	0,031	20,48
Mb 2.1	WC	Non bleached	Non bleached	1,017	0,091	11,18
Mb 2.2	WC	Non bleached	Non bleached	0,544	0,049	11,10
Mm 1.1	MP Highveld	Non bleached	Non bleached	0,932	0,049	19,02
Mm 1.2	MP Highveld	Non bleached	Non bleached	0,675	0,036	18,75
Mm 2.1	MP Highveld	Non bleached	Non bleached	0,867	0,049	17,69
Mm 2.2	MP Highveld	Non bleached	Non bleached	0,674	0,030	22,47
Mm 3.1	MP Highveld	Bleached	Bleached	0,987	0,055	17,95
Mm 3.2	MP Highveld	Non bleached	Bleached	0,700	0,020	35,00
Mm 4.1	MP Highveld	Non bleached	Non bleached	0,936	0,047	19,91
Mm 4.2	MP Highveld	Non bleached	Non bleached	0,510	0,026	19,62
Pb 1.1	WC	Non bleached	Bleached	1,832	0,103	17,79
Pb 1.2	WC	Non bleached	Non bleached	1,104	0,061	18,10
Pb 2.1	WC	Bleached	Bleached	1,910	0,047	40,64
Pb 2.2	WC	Non bleached	Bleached	0,717	0,015	47,80
Pb 3.1	WC	Bleached	Bleached	1,088	0,060	18,13
Pb 3.2	WC	Non bleached	Bleached	0,938	0,059	15,90
Rk 1.1	WC	Non bleached	Non bleached	0,960	0,060	16,00
Rk 1.2	WC	Non bleached	Non bleached	0,688	0,042	16,38
Rk 2.1	WC	Bleached	Non bleached	1,215	0,111	10,95
Rk 2.2	WC	Non bleached	Non bleached	0,607	0,034	17,85
Rk 3.1	WC	Non bleached	Non bleached	1,672	0,118	14,17
Rk 3.2	WC	Non bleached	Non bleached	0,564	0,032	17,63
Rk 4.1	WC	Non bleached	Non bleached	2,846	0,245	11,62
Rk 4.2	WC	Non bleached	Non bleached	0,977	0,069	14,16
Us 1.1	MP Highveld	Non bleached	Non bleached	1,549	0,113	13,71
Us 1.2	MP Highveld	Non bleached	Non bleached	0,970	0,076	12,76
Us 2.1	MP Highveld	Non bleached	Non bleached	0,979	0,062	15,79

**Appendix 4.7 (continued).** The organic carbon and nitrogen percentages of each of the sampled soil horizons and their calculated C:N ratio.

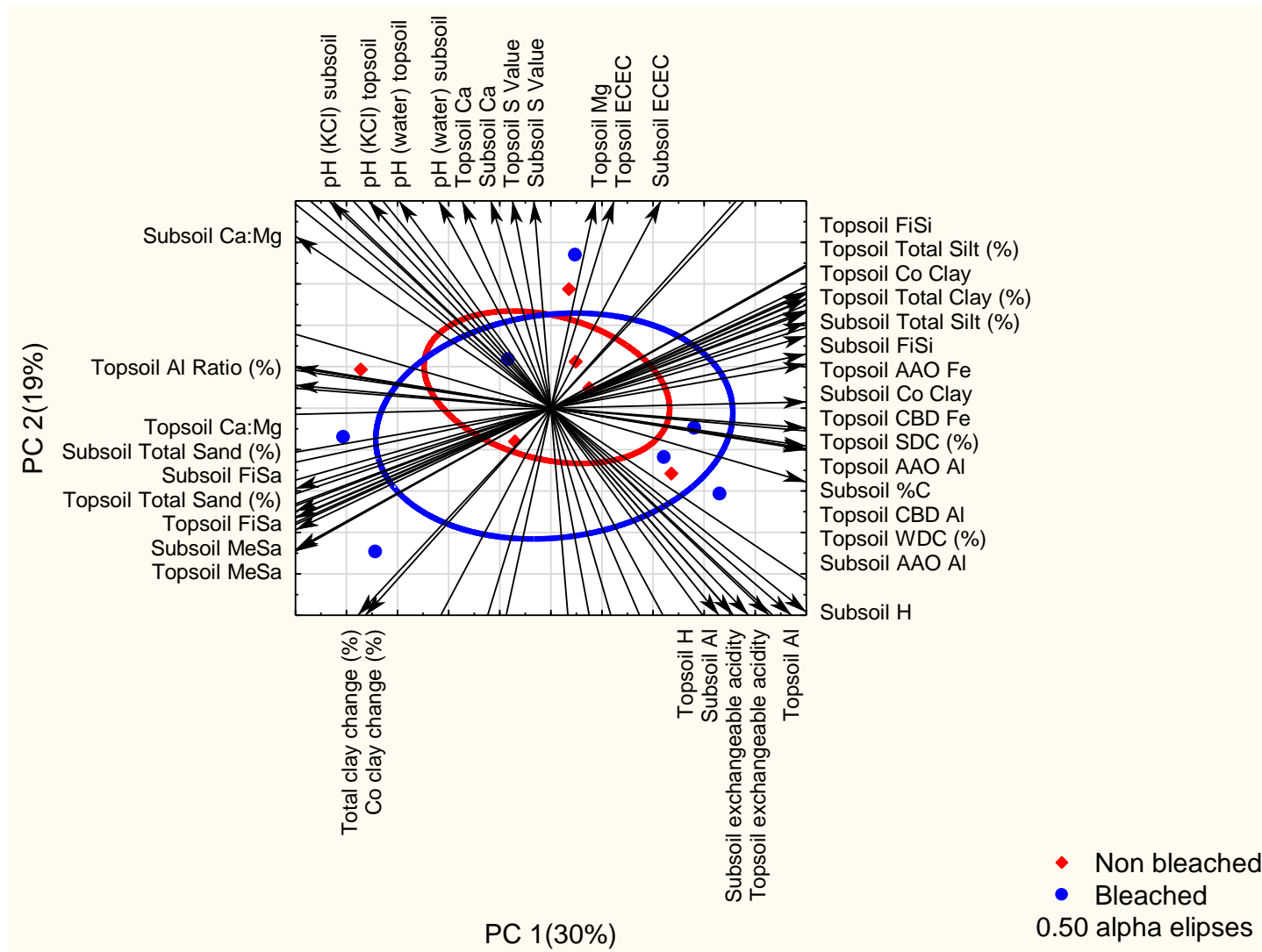
Profile	Location	Colour Condition: Perceived	Colour Condition: Measured	C %	N %	C:N
Us 2.2	MP Highveld	Non bleached	Non bleached	0,786	0,045	17,47
Us 3.1	MP Highveld	Bleached	Bleached	1,003	0,068	14,75
Us 3.2	MP Highveld	Bleached	Bleached	0,874	0,033	26,48
W3 1.1	WC	Non bleached	Non bleached	0,872	0,089	9,80
W3 1.2	WC	Non bleached	Non bleached	0,649	0,074	8,77



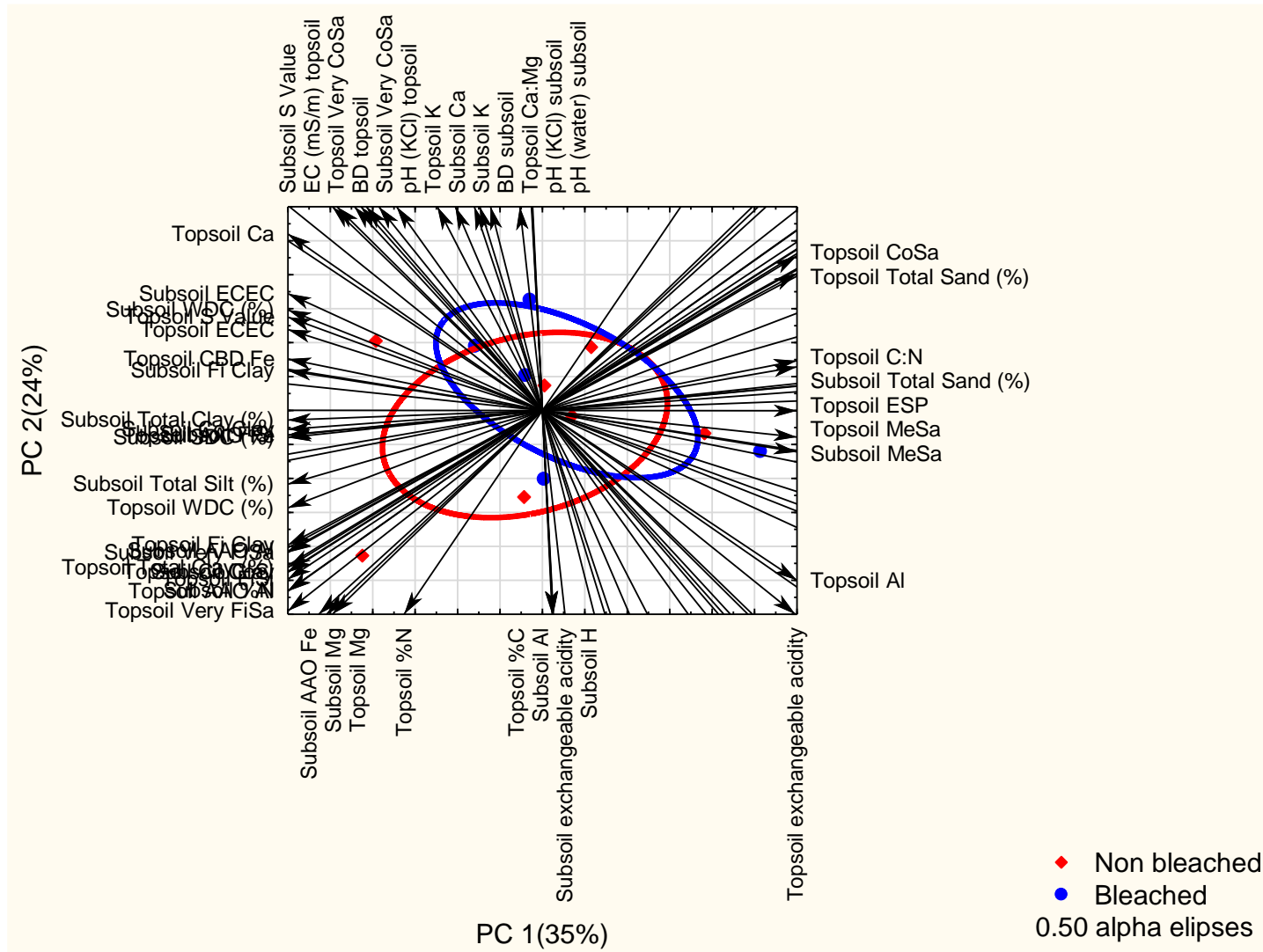
**Appendix 4.8** – The generated Principle Component Analysis biplots.



**Appendix 4.8 (1).** The generated PCA biplot for all the determined chemical and physical characteristics of the sampled bleached and non-bleached profiles combined.

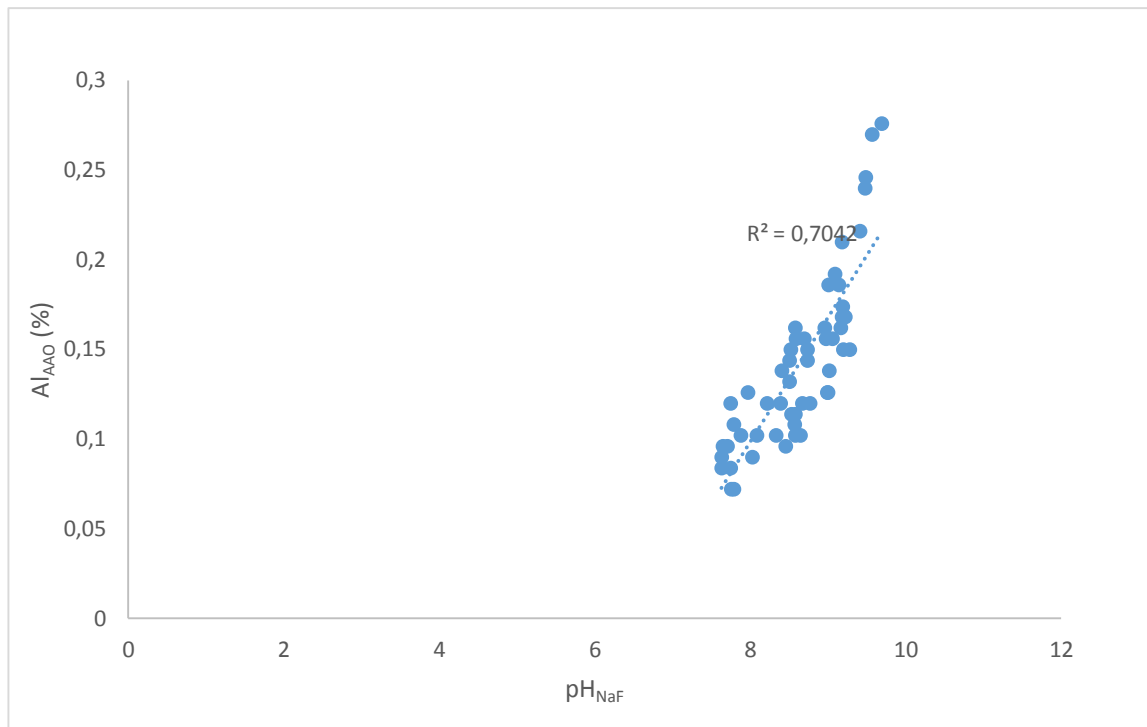


**Appendix 4.8 (2).** The generated PCA biplot for all the determined chemical and physical characteristics of the sampled bleached and non-bleached profiles in the Western Cape.



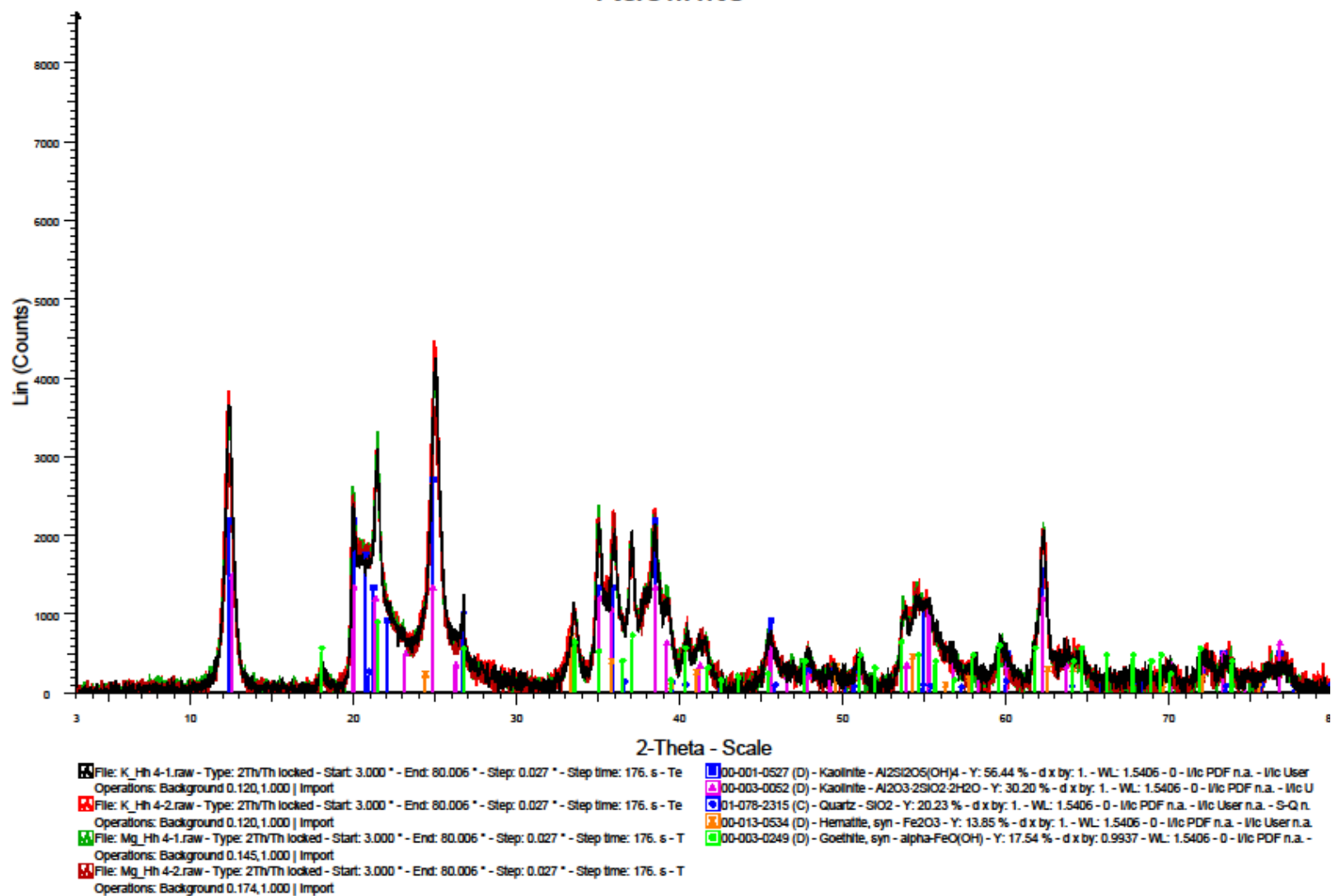
**Appendix 4.8 (3).** The generated PCA biplot for all the determined chemical and physical characteristics of the sampled bleached and non-bleached profiles in the Mpumalanga Highveld.

**Appendix 4.9** – The calculated relationship between the measured  $pH_{NaF}$  and  $Al_{AAO}$ .



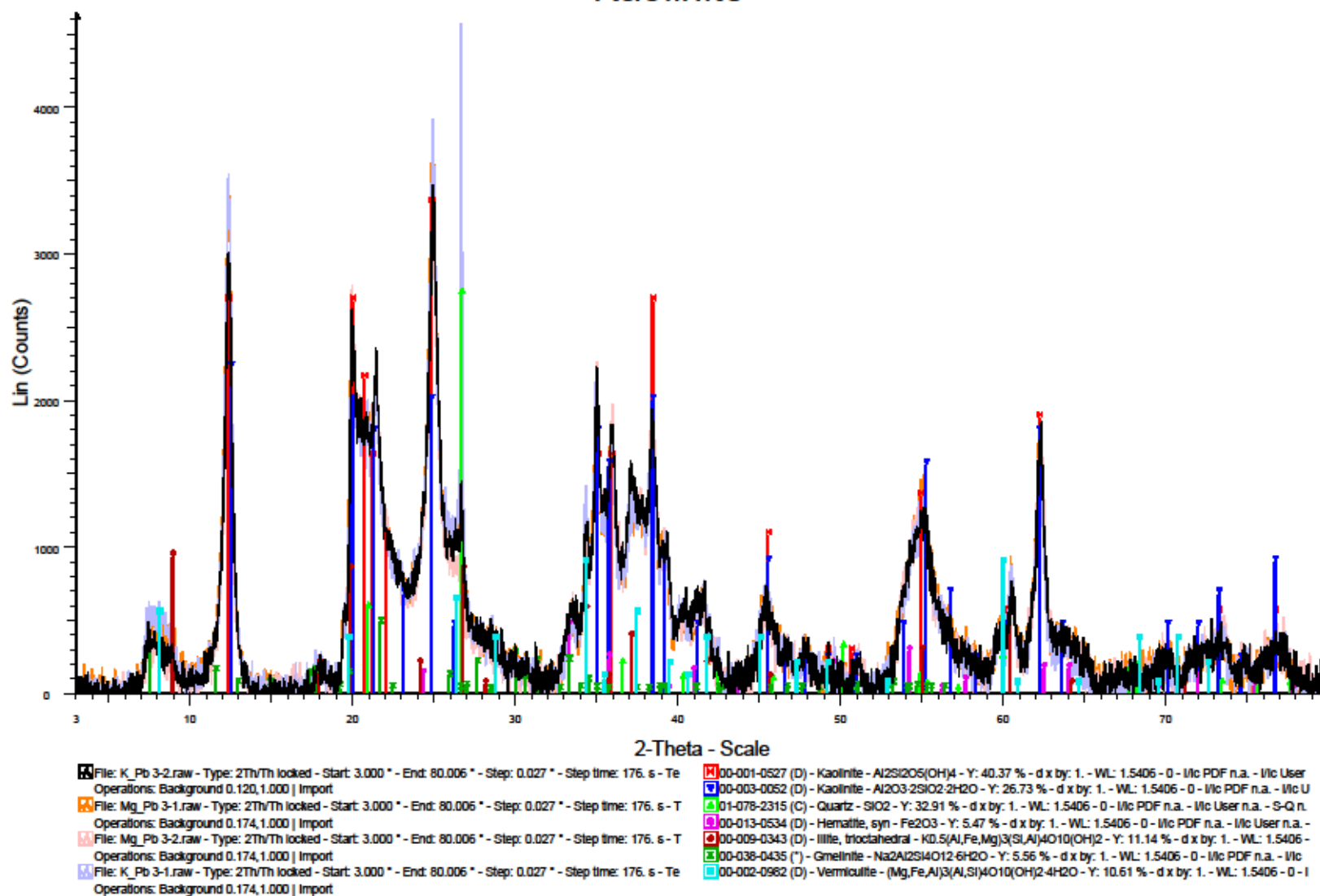
**Appendix 4.9.** The calculated correlation between the determined  $pH_{NaF}$  and  $Al_{AAO}$  of all the soils horizons sampled in the Western Cape and Mpumalanga Highveld.

## Kaolinite



Appendix 4.10. XRD clay mineralogy of K- and Mg-saturated Hh 4 samples.

## Kaolinite



Appendix 4.10. XRD clay mineralogy of K- and Mg-saturated Pb 3 samples.