

PROPERTIES OF BLEACHED TOPSOILS ON APEDAL SUBSOILS: ANALYSIS FROM THE LAND TYPE PROFILE DATABASE

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Declaration

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ABSTRACT

Bleached topsoils that occur on red and yellow-brown apedal subsoils are poorly understood and taxonomically they are not distinguishable from their non-bleached counterparts. Bleaching of soils is an important pedological indicator since it can reflect a soils water status. Bleached topsoils are more prone to erosion and degradation than their non-bleached counterparts, thus recognising these features is important. Bleaching is also identified by its colour, thus precise and objective colour measurement procedures are required to correctly identify them. The two mechanisms responsible for bleaching are proposed to be iron (Fe) reduction and clay dispersion.

The overall aim of this study was to use the data available in the Profile Database to understand the spatial and geomorphic distribution of bleached apedal profiles as well as assess their lithological, chemical, physical, spectral and subsoil colour properties to provide clues on their genesis. This will allow the diagnostic criteria for their correct identification to be based on scientific understanding and also to provide a scientific basis for these bleached soils use and protection.

The study made use of pre-existing data from the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System. Data from 725 soil profiles, with complete chemical and physical analysis, that contained red and yellow-brown apedal and neocutanic subsoils were selected for the study. Subsamples of the A and B horizon from each profile were collected from the soil store of the ISCW. Soil colours were measured both visually with Munsell colour charts and spectroscopically with a Konica-Minolta spectrophotometer. This colour data was used to classify the soils into bleached and non-bleached categories by following the criteria outlined in the South African soil classification system.

The effectiveness of visual colour measurement guidelines as outlined by the Munsell colour system and Food and Agricultural Organization (FAO) was evaluated by comparing visual measurements made in the laboratory and in natural daylight (outdoor) conditions. From the results there seems to be no great difference between soil colour measurements made in visual natural daylight and laboratory conditions. Visual colour measurements were also correlated to spectroscopic colour measurements. It was found that the spectrophotometer tended to make soil hues redder in 32% of the observations when compared to visual laboratory and natural daylight observations. Spectroscopic chroma observations showed 0% total agreement with both visual laboratory and natural daylight observations. When compared, the spectrophotometer tends to designate lower chroma values to soils than both

visual laboratory and natural daylight colour measurements would. This means the human eye tends to make soil colour more colourful than the spectrophotometer.

The weak relationships between soil pigmenting properties and spectroscopically measured colour components showed that soil colour is a complex expression of both physical and chemical soil components and thus cannot be related to individual soil properties. The wide geographical spread of these soils might be the cause of poor soil property-colour component relationships observed.

The geographical location of the soils used for this study did not seem to play a significant role in the occurrence of bleached topsoils in different landscapes. The occurrence of topsoil bleaching seemed to be significantly related to parent materials, with the frequency of bleaching being highest in siliceous lithologies and lowest in mafic lithologies. This might explain why bleached topsoils showed the tendency to develop in soils with low reducible Fe and exchangeable magnesium percentage (EMP). Clay movement from the A to B horizon showed no significant trends in terms of bleaching, which was also the case for exchangeable sodium percentage (ESP). In this study the results for clay movement and ESP thus does not support clay dispersion as a possible mechanism for topsoil bleaching. Bleaching tended to increase with a decrease in base saturation, with the highest incidences of bleaching being on dystrophic soils, which in turn could also relate to climate and soil acidity.

The highest occurrence of topsoil bleaching took place on yellow-brown apedal subsoils (66%) and in the Avalon soil form (79%). These results might provide evidence for topsoil bleaching to occur in soils with wetter water regimes, since Avalon soils are usually found in wetter landscape positions. It is recommended that the South African Soil Classification Working Group should consider adding bleaching as a family criteria to soil forms containing yellow-brown apedal subsoils.

OPSOMMING

Gebleikte bogronde wat voorkom op rooi en geel-bruin apedale ondergronde word swak verstaan en taksonomies is hul nie onderskeibaar van hul nie-gebleikte ewivalente nie. Verbleiking is 'n belangrike pedologiese aanwyser aangesien dit die grond se water toestand weerspieël. Gebleikte bogronde is ook meer geneig tot erosie en agteruitgang as hul nie-gebleikte ekwivalente. Verbleiking word geïdentifiseer aan sy kleur, dus word akkurate en objektiewe kleur meting prosedures benodig om hul korrek te identifiseer. Die twee voorgestelde meganismes verantwoordelik vir verbleiking is yster reduksie (Fe) en klei dispergering.

Die oorkoepelende doel van hierdie studie was om gebruik te maak van data wat in die Profiel Databasis beskikbaar was om sodoende die ruimtelike en geomorfologiese verspreiding van gebleike apedale grondprofile te verstaan, sowel as om hul litologiese, chemiese, fisiese, spektrale en ondergrond kleur eienskappe te evalueer om so dus leidrade oor hul ontstaan te kan voorsien. Dit sal die diagnostiese kriteria vir die korrekte identifisering van gebleikte gronde gebaseer laat wees op grond van wetenskaplike begrip wat ook 'n wetenskaplike basis sal bied vir die gebruik en beskerming van hierdie gebleikte gronde.

Die studie het gebruik gemaak van reeds-bestaande data uit die LNR (Landbou Navorsings Raad) - Instituut vir Grond, Klimaat en Water (IGKW) – Grondprofiel Informasie Sisteem. Data van 725 grondprofile, meerderheid wat ingesamel is tydens die Land Tipe Opname, met volledige chemiese en fisiese analyses wat rooi en geel-bruin apedale en neokutaniëse ondergronde bevat was geselekteer vir hierdie studie. Submonsters van die A- en B-horisonte van elke profiel was ingesamel uit die grond stoor van die IGKW. Grondkleure is visueel gemeet met Munsell kleurkaarte en spektroskopies gemeet met 'n Konica-Minolta spektrofotometer. Hierdie kleur data is dan gebruik om gronde in gebleikte of nie-gebleikte kategorieë te plaas deur om die kriteria te gebruik wat uiteengesit is in die Suid-Afrikaanse Grondklassifikasie Sisteem.

Die doeltreffendheid van visuele kleur metings riglyne soos die uiteengesit deur die Munsell kleur stelsel en Voedsel- en Landbou-Organisasie (FAO) is geëvalueer deur om korrelasies te maak tussen verskillende visuele kleur metings kondisies (laboratorium en natuurlike daglig (buite)). Die resultate het getoon dat daar geen betekenisvolle verskille was tussen visuele grondkleur metings wat gemaak is in natuurlike daglig en laboratorium kondisies nie. Visuele kleur metings is ook gekorreleer met spektroskopiese kleur metings. Die resultate het getoon dat die spektrofotometer geneig was om grond skakerings rooier te maak in 32% van die waarnemings in vergelyking met die visuele laboratorium en natuurlike daglig waarnemings.

Die spektroskopiese chroma waarnemings het 0% totale ooreenstemming getoon met beide van die visuele kondisies se chroma waarnemings. Die spektrofotometer was meer geneig om laer chroma waardes aan gronde toe te skryf in vergelyking met visuele laboratorium en natuurlike daglig chroma kleur metings. Dit mag beteken dat die menslike oog geneig is om grondkleur meer kleurvol te maak in vergelyking met die spektrofotometer.

Die swak verhouding tussen grond pigmenterings eienskappe en spektroskopiese gemete kleur komponente het getoon dat grondkleur 'n komplekse uitdrukking is van beide fisiese en chemiese grondkomponente en kan dus nie betrekking hê tot individuele grondeienskappe nie. Die geografiese verspreiding van die gronde in hierdie studie mag dalk die oorsaak wees vir die swak grondeienskap-kleur komponent verhoudings wat waargeneem was.

Die geografiese ligging van die gronde wat gebruik was vir hierdie studie het nie 'n betekenisvolle rol gespeel in die voorkoms van gebleikte bogronde in verskillende landskappe nie. Dit bleik asof daar 'n beduidende tendens is vir gebleikte bogronde om op sekere moedermateriale te ontwikkel. Silikahoudende gesteentes het die hoogste frekwensie van verbleiking getoon en mafiese gesteentes die laagste frekwensie. Hierdie resultate mag dalk verduidelik hoekom gebleikte gronde geneig is om in gronde met lae reduseerbare yster (Fe) vlakke en uitruilbare magnesium persentasie (UMP) te ontwikkel. Klei beweging van die A tot B-horison het geen beduidende verskille getoon in terme van verbleiking nie, wat ook die geval was vir uitruilbare natrium persentasie (UNP). Die resultate vir klei beweging deur 'n profiel en vir UNP ondersteun dus nie klei dispergering as die meganisme verantwoordelik vir bogrond verbleiking in hierdie studie nie. Verbleiking het ook geneig om toe te neem met 'n afname in basisversadiging, met die hoogste voorkoms van verbleiking op distrofiese gronde wat dalk verband mag hou met klimaattoestande.

Die hoogste frekwensie van bogrond verbleiking het voorgekom op geel-bruin apedale ondergronde (66%) en in die Avalon grondvorm (79%). Hierdie resultate mag dalk bewyse lewer dat bogrond verbleiking meer geneig sal wees om in natter gronde te ontwikkel, aangesien Avalon gronde gewoonlik geassosieer word met natter landskap posisies. Daar is voorgestel dat die Suid-Afrikaanse Grondklassifikasie Werkgroep dit moet oorweeg om verbleiking as 'n familie kriteria te erken in grondvorms wat geel-bruin apedale ondergronde bevat.

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CHAPTER 1

1. General introduction

In the current South Africa Soil Classification System, Soil Classification: A Taxonomic system for South Africa (Soil Classification Working Group, 1991), the morphological property, soil colour is used to help differentiate between different soil types, properties and processes. It is an important diagnostic criteria for a number of soil horizons, which include the Melanic A horizon, red and yellow-brown apedal B horizons, red structured B horizons and the E horizon. Colour in terms of bleaching is also recognized at a family level for orthic A horizons in certain forms. Currently the classification system of South Africa (Soil Classification Working Group, 1991) does not accommodate bleached A horizons overlying well-drained red and yellow-brown apedal B subsoil horizons. However, a recent study by Van der Waals (2013) shows that such soils (called bleached apedal profiles, hereafter) do exist. The genesis of these bleached A horizons and the effect of bleaching on the behaviour and management of such profiles, are not well understood. Understanding the development of such bleached topsoils are vitally important since it will allow classification of such soils to be based on scientific principles instead of subjective assumptions. Since 90% of all topsoils in South Africa recorded in the Land Type Survey (Soil Classification Working Group, 1991) were classified as orthic A horizons the correct identification and classification of the bleached variants is important.

Bleached A horizons are recognised on a family level in non-hydromorphic soil profiles which contains the following subsoils: cutanic subsoils, hard plinthic subsoils, neocarbonate subsoils and hard rock. An explanation for the South African Soil Classification System (1991) not recognizing bleached A horizons on red and yellow-brown apedal B horizons has not been documented but it is assumed to be due to the understanding that apedal soils are considered to be well-drained and uniform in colour due to their stable clay phase. Which suggests that these soils are not subjected to long periods of water saturation. Bleached topsoils overlying red and yellow-brown apedal soils do however occur, but because no classification guidelines exist for these bleached apedal profiles, various approaches are used when confronted with this problem. For example, in the Western Cape red and yellow-brown apedal subsoils are often classified as neocutanic subsoils to accommodate the overlying bleached A horizon, while in the Mpumalanga Highveld topsoil bleaching is usually ignored and the subsoil is classified as either being a red or yellow-brown apedal B horizon instead of a neocutanic B horizon. The fact that no classification guidelines exist for apedal profiles containing bleached topsoils, could be due to subjective soil survey methodologies where horizon sequences are always considered in a vertical sequence from where it is assigned to a soil form. This is not

the case for bleached topsoils overlying yellow-brown and red apedal subsoils, where subsoils are deliberately classified with or without the acknowledgement of the overlying bleached A horizon. This results in one soil being classified as two different soil forms that are not associated with each other in terms of soil suitability. These various classification approaches represents a serious shortfall with the national soil classification system.

Topsoil bleaching is often associated with crusting and surface sealing, physical instability and low hydraulic conductivity making these topsoils more prone to erosion (Ellis, 1984). Thus the recognition of bleached A horizons on a family level for other non-hydromorphic soils (cutanic subsoils, hard plinthic subsoils, neocarbonate subsoils and hard rock), has proved to be a valuable tool in suitability evaluations, identification of what are considered to be “problem” soils and the development of soil surface management practices, especially for irrigated crop production (Lambrechts & MacVicar, 2004). According to Van der Waals (2013) bleached topsoils may play an important role in hillslope hydrology and correct identification of these topsoils is essential to ensure adequate water management and modelling of catchment areas associated with mining activities as is seen in the Mpumalanga Highveld.

Bleaching is usually associated with the process of reduction which involves periodic saturation leading to a loss of Fe and possibly eluviation of clay giving it its greyish colour in the dry state. For this reason the need to recognise bleaching in certain soils was overlooked or considered unnecessary since topsoil bleaching would be expected. Local research conducted in the Mpumalanga Highveld by Van der Waals (2013) on soil colour and hydromorphology, placed emphasis on the catena concept that helps us understand the relationship between periods of water saturation and the loss of Fe from the profile. It was reported that red soils occur on crest positions, yellow soils on midslope positions and bleached topsoils on valley bottom positions, thus supporting our current understanding of bleaching. From this, waterlogging of soils in semi-arid regions, such as the Karoo, should then rarely occur. This leads to question whether different bleaching mechanisms exist in different regions of the country and if all bleached topsoils show the same instability as those described by Ellis (1984). Under specific conditions topsoil bleaching may also be associated with the process of podzolization.

Although topsoil bleaching is recognised for certain soil forms, our understanding of what causes it and how it effects soils is poor. Reduction as a mechanism for topsoil bleaching thus does not align with the fact that apedal subsoils are considered to be mature, stable and well-drained soils. While the mechanisms of topsoil bleaching, are likely to be complex and would require numerous pedological studies, it is often useful to start with data that is already available. The Agricultural Research Council’s Institute for Soil, Climate and Water (ARC-

ISCW) provides such data that also forms part of the so called Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System. This database includes the physical and chemical information of all soil profiles sampled during an extensive field survey that began in South Africa early in the 1970's. This field survey was collectively called the national Land Type Survey. The greatest advantage of the Land Type Survey is the fact that every part of the country was visited (Paterson et. al., 2014). As the field investigation phase of the Land Type Survey progressed, it also led to further advancements in soil classification, which resulted in the publication of the second and also current edition of the South African Soil Classification System (1991). The products of the Land Type Survey were initially a series of 1:250 000 scale overlay maps (Paterson et. al., 2014). Each map sheet, or combination of one or more adjoining map sheets, was accompanied by a printed memoir book, which provided information on all the land types, climate zones and modal soil profiles occurring on that map (or maps) (Paterson et. al., 2014). The information provided in the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System creates an opportunity to possibly establish some of the controls responsible for topsoil bleaching on well-drained apedal subsoils.

1.1 Aims and objectives

The overall aim of this study was to use the data available in the Profile Database to understand the spatial and geomorphic distribution of bleached apedal profiles as well as assess their lithological, chemical, physical, spectral and subsoil colour properties to provide clues on their genesis. In order to achieve this aim the following objectives were set:

- i) Compare methods of soil colour measurement to understand the differences between visual and spectroscopically measured colour.
- ii) Attempt to correlate selected soil chemical parameters with soil colour variables.
- iii) Establish the occurrences of bleached profiles in relation to geomorphic attributes, lithology and chemical and physical properties.
- iv) Establish the occurrence of topsoil bleaching in relation to various subsoil types and soil forms.

1.2 Thesis layout

This study is has been divided into five chapters. After the general introduction (Chapter 1), Chapter 2 gives an overview of soil colour measurement, colour space models and factors

influencing soil colour. Chapter 3 gives information on the soils used in this study, also the different methods used for colour analysis and post-processing of data. Chapter 4 assesses soil colour measurement in different conditions and the relationship between various soil properties and different colour parameters. Chapter 5 focuses on the relationship between bleached A horizons and geomorphological, lithological, physical and chemical properties of soils. The General Conclusions summarises the work and provides recommendations for classification and future work.

CHAPTER 2

2. Quantifying soil colour: colour space models, influential soil parameters and pigmenting processes

2.1 Introduction

Soil colour is an important morphological property when classifying soils. Unfortunately it is often treated as an afterthought in most soil classification systems. Due to this negligence, soil colour still remains poorly understood. The reason for this may be because soil colour, and more so colour science is a complex discipline that stretches across multiple disciplines including physiology, psychology, physics, chemistry and mineralogy. Regardless of soil colour being correlated to different measurable soil parameters, it is found that soil colour cannot be measured with great precision or accuracy (Bigam & Ciolkosz, 1993).

In this chapter the concept of colour science will be discussed which includes the physical, psychophysical and psychological aspects of colour perception. Also discussed is the use of different colour space models, which enables researchers to quantify colour. This data can then be used to perform statistical analysis on colour parameters. The current guidelines followed for soil colour measurement in the field and laboratory will also be specified. This includes the technology available for accurate soil colour measurement. Since data collected from colour measurements is seen as sensory data, there are specific and more effective statistical methods that can be used to aid in data processing. These methods will be discussed briefly. The soil properties and pigmenting agents responsible for soil colour will also be investigated. Remote sensing as a spatial tool for identifying these pigmenting properties in the field will also be discussed briefly.

2.1.1 Colour science and soils

The physics of light travelling through the neurophysiology of the eye and brain, including human perception are all complex processes that form the concept of human colour vision. Colour can thus be summarized as the result of a specific light source, the object from which the light reflects and the eyes of the observer (Atkinson & Melville, 1985). Colour is a natural sense and not a physical property of a specific object or the physical nature of light. Colour science would then be classified as a sensory science.

Light can be seen as a special form of energy that transmits as a wave with an electric field, which is perpendicular to a magnetic field. Both fields travelling perpendicular to the direction of travel, creating the concept of light being electromagnetic radiation (Orna, 2013). The human eye is only sensitive to electromagnetic radiation that falls within the 380 to 760 nm spectrum range (Rossotti, 1983). Outside this wavelength range the radiation is considered not to be useful for the human eye. Before we can understand the colour of soils and how to accurately measure them, we first need to understand the fundamentals of colour science.

2.1.1.1 Light source

Spectral energy distribution curves are energy ranges emitted by every source of illumination or light across the energy spectrum. The human eye will perceive a light source which emits constant radiant power over the limited response range of the human eye (380-760nm) as “white” or achromatic light (Orna, 2013). An example would be a light source which emits energy predominantly in the red region of the spectrum and a small amount in the blue-green region of the spectrum. This will then be perceived by the human eye as reddish-yellow. The figure below (Figure 2.1) shows the spectral energy range for sunlight also called visible light, restricted to the 400-700 nm range. The variation is minimal for the intensity of radiation energy that sunlight or visible light over this wavelength range will experience. The perception of colour is thus dependent on visible radiant energy, meaning colour can be defined as a characteristic of light (Wyszecki & Stiles, 2000) Different illuminating or lighting conditions whether being sunlight conditions outdoors or different lightbulbs used for indoor use, all will have different perceptual effects on an objects colour.

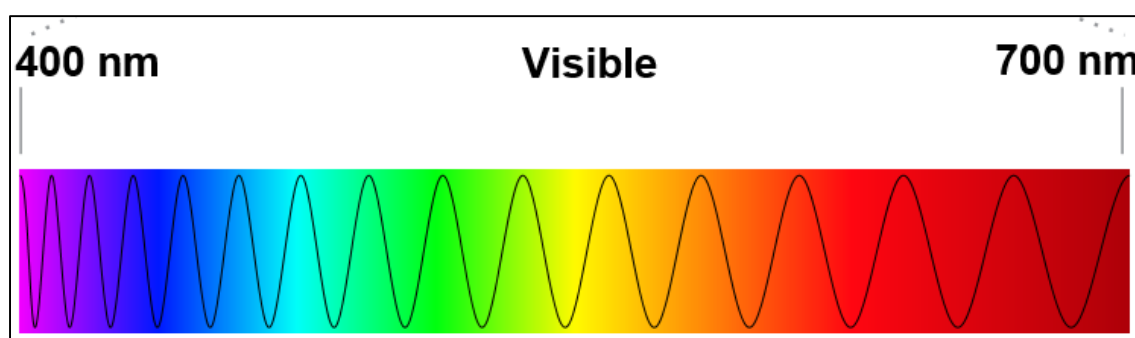


Figure 2.1: Linear range of the visible light spectrum (Commons, 2011)

2.1.1.2 Object from which the light will reflect

The object from which light will reflect can be in the gaseous, liquid or solid phase. When light interacts with any object it is modified and can undergo changes such as reflection,

transmission, refraction, dispersion, scattering, absorption, diffraction, polarization and interference (Orna, 2013). Important to note is that these interactions can lead to perceived colour changes. In soils these colour changes can also be observed and will be better understood once the effect of physical and chemical properties of soil colour is discussed.

When light is reflected from a smooth object the reflected rays will be at an angle equal to that of the light emitted from a specific source. When the incoming light source are parallel rays, the reflected rays will also be parallel, since each ray will have a normal plane parallel to the normal planes of the other rays (Orna, 2013) (Figure 2.2a). If light should be reflected from a rough surface, such as soil, and the incoming rays be considered parallel, the resulting reflecting rays would not be parallel. The reason for this is because normal planes must be created perpendicular to the surface the incoming light source would strike. This type of reflection is called diffuse reflection (Figure 2.2b). Here the rays or reflecting light reaching the observer's eye would be much less, than would be the case if the object's surface was smooth. This limited amount of reflected light would then make the object appear to be duller than for an object with a smooth surface.

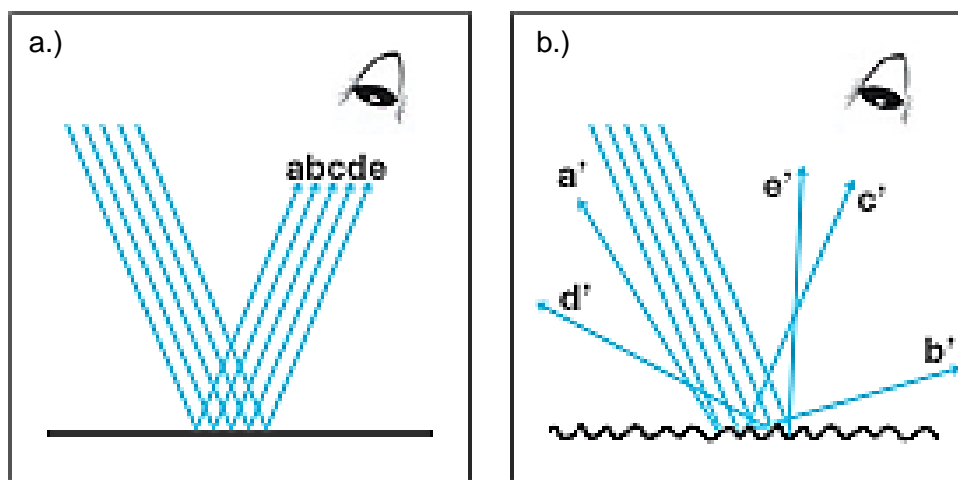


Figure 2.2 : a) Light reflected from smooth surface b) Light reflected from a rough surface (Diffuse reflection) (Konica Minolta, 2007)

The degree to which light is absorbed by an object depends on its atomic structure. Translucent materials such as milky quartz particles in soils will absorb almost no wavelengths of the visible spectrum and would rather allow the light to transmit through it. Since no single quartz particle found in soil has a smooth surface, the light being reflected, in this case diffused light from the particle's surface, is giving quartz the appearance of being white. For opaque materials such as organic material (OM) in soil, light will be totally absorbed by the OM. Which

means no visible wavelength is reflected back to the observer, giving the OM its dark/black colour. All these different interactions between visible wavelengths and objects discussed, can take place at the same time and to different degrees. These interactions lead to the overall appearance of an object.

2.1.1.3 Eyes of the observer and colour perception

When colour is perceived, it is the result of the light reflected or transmitted to the eye, from where a subjective, personal or conscious evaluation is made. This conscious response and the sensations experienced as a result of the colour characteristics of the light stimulating the eye, is very important to understand. When colour is measured by a hypothetical standard observer, for example, an instrument, it detaches colour from the perceptual variabilities of human beings and also removes the conscious aspect of colour. It is thus important to understand how a real human observer and hypothetically ideal observer would differ and experience the sensation of colour. By having some sort of understanding how the two observers function, the establishment of adequate colour measuring conditions can be implemented. Also by having a clearer understanding of how these different observers function, any differences in how humans and the ideal observer would measure colour, could then possibly be explained and colour measuring conditions can be improved on (Wyszecki & Stiles, 2000).

Light enters the human eye through the retina, and is where each individual observer will perceive colour differently. The retina consists of two classes of photosensitive cells, namely rods and cones that absorb light. Rods respond to differences in brightness, mainly in dark lighting conditions which makes them sensitive and very responsive to small changes in light energy. Cones are mainly effective in brighter lighting conditions and allows us to distinguish between different colour ranges (Rossotti, 1983). Cones can be subdivided into three types or pigments, each type stimulated by a primary colour (primary wavelengths) of the light stimulus, be it blue, green or red. The combination of these three primary colours allows us then to discriminate between different colours (Gordon, 1998). The highest density of cones are located at the centre of the retina, decreasing outwards towards the perimeter. When visually measuring colour, specifying the angle at which colour measurements should be taken is important, since the perception of colour will vary across the this field of view. Currently the standard viewing angle for making colour measurements are 2° and 10° (Edwards, 1975).

According to Edwards (1975), majority of the human population will respond more or less the same to a specific light stimulus. Colour measurement systems are based on this notion that the majority of humans (92%) will perceive colour identically. The assumption is then made

that colour measurement systems should represent all those who have “normal” colour vision (Edwards, 1975). The remaining 8% of the population would be people whose response to a light stimuli would be disregarded when developing a colour measurement system. Colour vision deficiencies include, colour blindness. This is a condition where an individual lacks one or more than one of the three types of receptor cones in the retina. This results in the individual not being able to perceive colour as a combination of the three prime colours, since one or more prime colour cone receptors are missing (Gordon, 1998). Perception of colour can also be influenced by age. The human crystalline eye lens undergoes yellowing with aging. This means that there will be a decrease in the light transmitted through the lens. According to a study by Gordon (1998), done on the effect of aging on colour vision, he found that age-dependent light losses from the eye was greatest in the blue end of the visible colour spectrum. This means that a higher proportion of short wavelengths (red colours) are absorbed by the eye.

All humans are different, and one would expect no individual to be biologically identical to another. Although colour measurement systems are based on the response of a “hypothetical” observer, each individual will have small differences, psychophysical or psychological, in the way they would perceive the colour of an object. The above factors discussed which contributes to the way colour is perceived will also affect the way colour of soil is measured. Whether it be visually or by instrument in the field or laboratory.

2.1.2 Colour space models and measurement of soil colour

As discussed in section 2.1.1.3, the photosensitive cells of the eye, called cones form sensations when the colour of an object is perceived, due to their response to the light stimulus entering the retina of the eye. The most important attributes or sensations created by a specific colour is its lightness (value), hue and colourfulness (chroma) (Ford & Roberts, 1998). Lightness or value is the lightness of a colour and is directly correlated with the total amount of light entering the eye and the proportion of light reflected by the object (Cassel & Daniels: 94). Hue is associated with the dominant wavelength of the light stimulus whether it be blue, red or green (Edwards, 1975). The colourfulness or chroma of a perceived colour is the degree to which it deviates away from white or neutral grey colours or the pureness of a specific hue (Cassel & Daniels: 94)

Since these colour sensations depend on the extent to which the three types of cones are stimulated by a physical stimulus, each of these three responses could then possibly be measured. This will result in a unique description for each colour sensation and can possibly enable a defined random response for each type of cone (Edwards, 1975). This will also make

it possible to calculate the effect of any light stimulus on the three types of cones, and allows the opportunity to create a model to measure colour in a three dimensional space (Rossel-Viscarra et. Al., 2006). A colour space is a method where you specify, create and visualise colour, using three coordinates or parameters (Ford & Roberts, 1998). Colour spaces do not identify a colour but rather the position of the colour within the space model being used.

There are multiple colour space models used within a range of different industries. In soil science the aim is to measure the colour of a soil by using space models that are designed to reflect our perception of colour, including its variations. In soil science the chosen colour space model should also allow the observer to perform numerical and statistical analysis (Rossel-Viscarra et. al., 2006). In this section the three most commonly used colour space models in soil science will be discussed. This includes the Munsell colour system that attempts to create perceived colour with equal differences, the *Commission Internationale de l'Eclairage* (CIE) $L^*a^*b^*$ and (Red, Green, Blue) RGB system that link spectral profiles of colours to the basic units of colour perception (Rossel-Viscarra et. al., 2006).

2.1.2.1 Munsell colour system

In soil science the colour of soil is primarily determined qualitatively by making using of Munsell soil colour charts. These charts are a collection of physical samples that helps the observer arrange and describe a specific colour (Atkinson & Melville, 1985). The aim of designing this system was to arrange the individual colour chips according to equal intervals of visual perception (Rossel-Viscarra et. al, 2006). This means the intervals are designed to accommodate when humans will detect a difference between adjacent colour chips. Each colour chip is made up of three variables i.e. Munsell hue, Munsell value and Munsell chroma. These variables represent, respectively, the dominant wavelength in the visible light source, the lightness and the saturation of the colour. These three variables or coordinates represent a perceptual colour space and cannot be used to quantitatively measure visible light, also making this system non-uniform (Rossel-Viscarra et. al., 2006).

According to the Munsell soil colour charts (2000) the following is said about the way soil colour should be assigned when using the charts:

“When recording soil colour the Munsell notation is used. Separate notations for hue, value and chroma, combined in that order forms a colour name. The hue is symbolised categorically by the letter abbreviation of the colour of the spectrum. The abbreviation is then preceded by numbers from zero to ten and within each letter range, the hue becomes more yellow and less red as the preceding number increase.

Munsell value is identified by the number range zero (black) to ten (white). Chroma is also specified on a numerical scale. Zero representing neutral grey colours and a value of 20, for the maximum which is seldom reached in the field of soil science.” (Munsell Color Company, 1980).

It should be noted that the Munsell value and chroma scales are arranged in such a manner that the difference between each chip is perceptually equal. However this does not mean the scales of the two variables are perceptually identical (Atkinson and Melville, 1985), for example one step increase in value does not perceptually “look” the same as one step increase in chroma. Munsell value and chroma are linear scales that can be represented on an orthogonal axes, whereas Munsell hue is a circular scale (Figure 2.3). This circle incorporates all possible hues and is divided into hundred unit steps, each with a 3.6° arc (Atkinson & Melville, 1985).

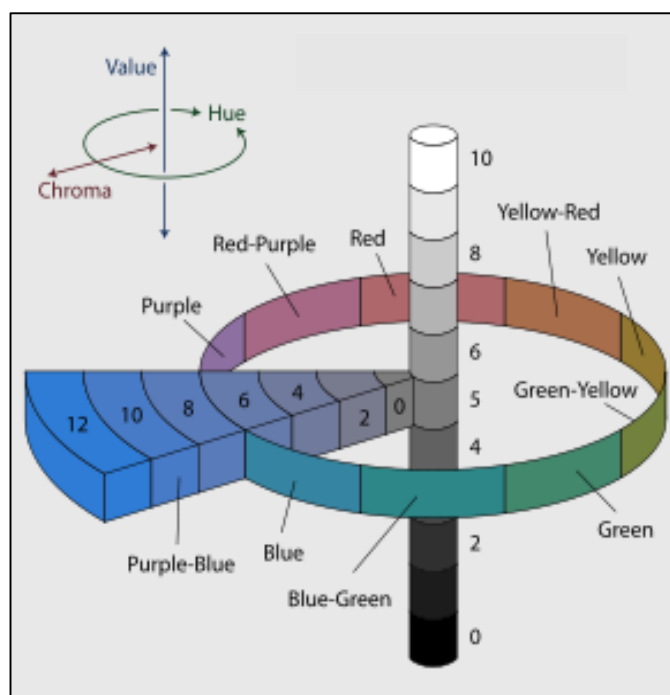


Figure 2.3: Graphic representation of Munsell Colour System (Commons, 2007).

To create a uniform colour space one has to assume that the perception of colour can be accurately represented by any variable related to Munsell hue, value and chroma and that these variables are appropriately scaled to create uniformity (Atkinson & Melville, 1985). When these requirements are met, Euclidean geometry can be applied in creating the so called Euclidean distance (ΔE), and would be a valid measure of perceived colour differences in this

uniform space. How Euclidean distances are applied when making use of the Munsell system or any other system, will be discussed in section 2.1.2.2.

The way colour, or in this case soil colour is recorded or notated when using the Munsell colour system, supplements as a useful abbreviation in field descriptions, expressing specific relations between colours and for statistical treatment of colour data (Munsell Color Company, 1980). Other features that makes the Munsell system as useful and acceptable as it is currently, is that the system is not limited to the range of colours reproducible by present day devices or systems (pixel gamut) (US Ink, 2000). More colourful chips are allowed to be produced as new technology develops. Another contributing feature is that the chips are produced according to very strict tolerances. Users can thus be assured that the description of each colour chip found in the new versions of the Munsell Book of Color are accurate and precise (Atkinson and Melville, 1985).

Adversely the Munsell system does not provide any standards for when soil colour is measured in different contexts (field or laboratory). When measuring soil colour under non-standard conditions, as outlined by the systems in the following sections, the perceived colour of the Munsell chips would appear quite different from what is expected from its notation (Committee on colorimetry, 1953).

*2.1.2.2 CIE $L^*a^*b^*$ measurement model*

The *Commission Internationale de l'Eclairage* (CIE) is responsible for establishing international standards for colour specification and instrumental colour measurements. In 1931 they proposed and recommended the first colour specification system. This system is only applicable in colour measurements made with a computerised machine or device combined with the appropriate software (Luo, 2006). The CIE system is defined by the three essential components of colour perception i.e. spectral distribution of the illuminating light source, spectral reflectance characteristics of the object and the spectral response characteristics of the device or observer (Atkinson & Melville, 1985). From this new specification system, colour could now be measured and described by using these three components of colour perception or tristimulus values (XYZ). These XYZ values indicate the amount of reference red, green and blue light necessary to match a specific colour of an object (Luo, 2006). With the measured XYZ values it is now possible to specify and match any colour with a specific set of light source- and observer conditions that allows the exchange of colour information by numbers. Due to the perceptual non-linearity of the XYZ colour space (Figure 2.4), the CIE created an approach towards a uniform colour system by respectively transforming the XYZ values (Luo, 2006).

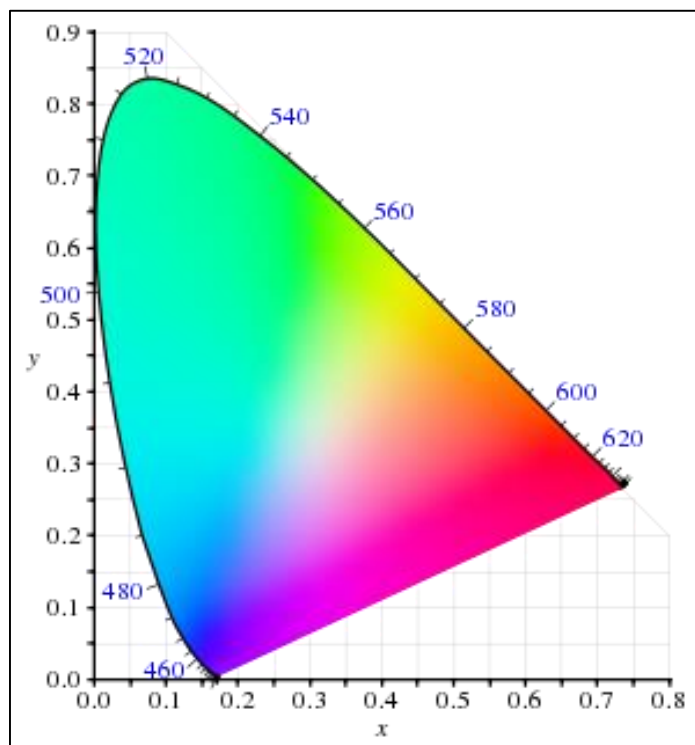


Figure 2.4: Representation of the non-linear CIE XYZ colour space model (Commons, 2009).

This new perceptually uniform colour space is called CIE $L^*a^*b^*$. In this notation L^* indicates lightness of an object that ranges from zero (black) to hundred (white) (Figure 2.5). The chromaticity coordinates, a^* represents the redness-greenness attributes of an object and the b^* represents the yellowness-blueness attributes (Figure 2.5) that range from -60 to +60 respectively (Rossel-Viscarra et. al., 2006). The $L^*a^*b^*$ model is more appropriate to use on objects with reflected colours, as is the case with soil colour. As was briefly mentioned in section 2.1, Euclidean geometry was also used by the CIE to create equations to calculate the numerical distance between any two colours in this uniform space (ΔE^*ab).

The CIE system cannot be related to any form of physical colour samples, and serves only the purpose of communicating if two colours will match based on their tristimulus values, L^* , a^* and b^* . Although the $L^*a^*b^*$ calculation formula is based on the colour vision of the human eye, colour differences calculated and obtained through the ΔE^*ab value and the human eye are evaluated differently. This is because colour discrimination by the human eye is very different from the colour differences defined by the CIE $L^*a^*b^*$ space model (Atkinson & Melville, 1985). This means that the human eye cannot differentiate the colours in certain regions of the colour space from others, even if they are different.

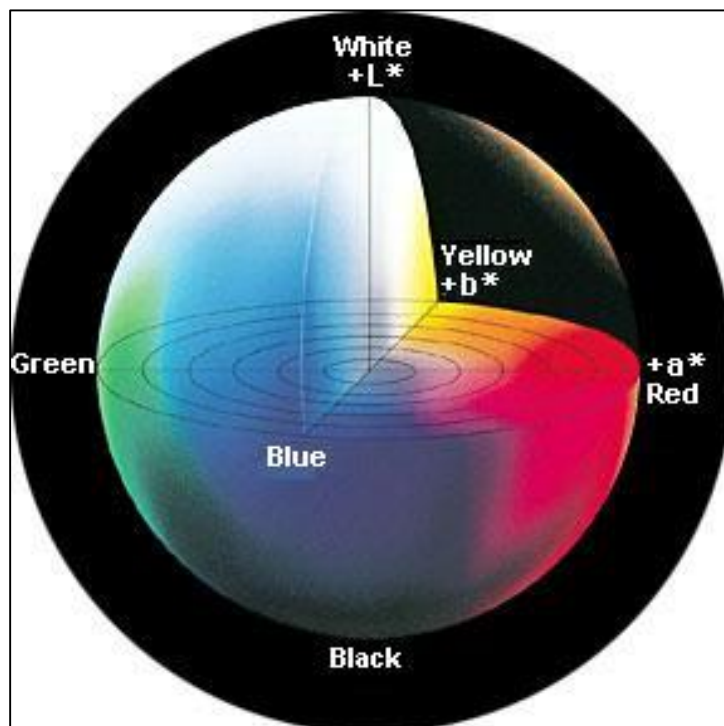


Figure 2.5: Representation of the CIE $L^*a^*b^*$ colour space model (Konica Minolta, 2007).

2.1.2.3 RGB System

The Red, Green and Blue (RGB) colour space is mostly used for computer graphics to create a colour image. This colour space is non-linear in terms of human colour perception. Producing colour using this space model, the additive or subtractive mixture of red, green and blue's spectral properties are used. The monochromatic primary stimuli or wavelength for each of these primary colours being 700 nm, 546 nm and 436 nm, respectively (Rossel-Viscarra et. al., 2006). This system can be visualised as a cube, with red, green and blue represented on three axes (Figure 2.6). Grey colours are also accounted for on the main diagonal axis. On this diagonal axis the colour system is quantified by numeric tristimulus R, G, B values. Together the three values create a black colour when the three values equal to zero ($R=G=B=0$) and a white colour when the three values equal to 255 ($R=G=B=255$) (Ford & Roberts, 1998).

When making use of remote sensing in soil science the RGB space model is primarily used because the tristimulus values R, G and B can easily be extracted from satellite images (Rossel-Viscarra et. al., 2006). When describing soil colour, the main disadvantage of using the RGB space model is the high degree of correlation illuminating intensities have on each of the three variables (Rossel-Viscarra et. al., 2006). Decorrelating RGB data (DRGB) will

transform it into three statistically independent coordinates. These transformed coordinates, hue, light intensity and chromatic information (H_{RGB} , I_{RGB} and S_{RGB}) are good approximations to the perceptual parameters of the Munsell colour system, Hue, Value and Chroma (Rossel-Viscarra et. al., 2006). Making the DRGB model more stable than the RGB model when changes do occur in term of illumination.

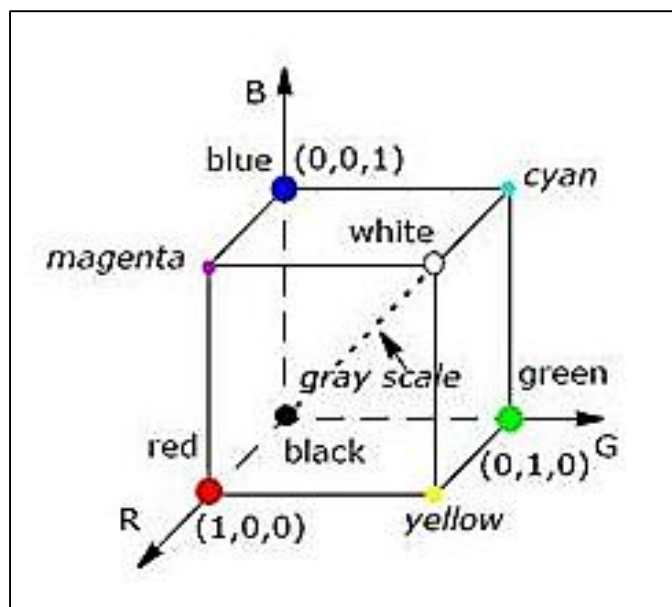


Figure 2.6: Spatial representation of the RGB Colour Space Model. The number 1 in brackets, represents the number 255 (Public Lab, 2014)

2.2 Soil colour measurement

Assigning colour to soil significantly aids soil scientists to characterize and/or differentiate between soils, and also forms a standard part of soil surveys and research. The accepted standard method for measuring soil colour is by visually comparing a soil sample with a set of colour chips, of which the Munsell soil colour charts are the most familiar amongst soil scientists (Barron &Torrent, 1993).

As discussed in section 2.1.1, the way humans perceive the colour of objects will be influenced by the specific light source, the object from which the light reflects and the eyes of the observer. When visually matching a soil colour to a Munsell colour chip, it would be highly unlikely for the soil to have the same spectral reflectance characteristics as any of the Munsell colour chips. It is, however, possible for humans to make an approximate colour match between a soil and a Munsell colour chip under specific lightening conditions even though their spectral reflectance characteristics do not match. For instance, if the soil and the Munsell chip

should be placed in different lightening conditions they would not match if viewed by the same human observer. This phenomenon is termed metamerism (Barron & Torrent, 1993). If the soil and the colour chip would have had the same spectral reflectance characteristics, they will always have the same perceived colour, regardless of the lightening conditions.

It is understandable why standard measurement conditions are needed when visually matching a soil colour to a Munsell colour chip, especially in field and laboratory conditions. It would be expected that these conditions can be met more easily in laboratory conditions than in field conditions. Although the visual measurement of soil colour in field and laboratory conditions may lead to the misidentification of a colour, following standard measurement conditions would decrease the possibility of making measurement errors.

2.2.1 Soil colour measurement using the Munsell System in the laboratory and field

2.2.1.1 Conditions for field visual colour measurements

Notes on visual colour measurement as given by the Munsell soil colour charts and United States Department of Agriculture (USDA), better known as the Soil Survey Manual, are not sufficiently accurate. As expected this is because not one of these publications give clear standardized guidelines for the lighting conditions and the physical state of the soil sample under which visual soil colour measurements should be made. The Munsell soil colour charts give guidelines that focuses more on visual colour measurement, where the USDA will be more focused on the physical state of the soil (Atkinson & Melville, 1985). Regardless of these shortcomings, the guidelines or procedures given by each of these publications are as follows:

According to the Munsell colour chart guidelines, when visually determining the colour of a soil, the soil sample should be held directly behind the opening that separates individual colour chips from each another. The black, grey and white viewing masks provided in the Munsell colour charts should be used to facilitate soil- colour chip matching. The black viewing mask for dark soil samples and the grey and white viewing masks for intermediate and light soil samples.

Difficulties encountered when using the Munsell soil colour charts include: i.) selecting the correct hue chart, ii.) determining colours that are between the hues provided on the charts and iii.) being able to distinguish between value and chroma when the chroma of a soil sample is strong or high (very red or yellow soil). In addition extremely dark colour chips with low values and high chroma are not included in the charts, and occasionally these colours are necessary to identify moist soil colours (Munsell Color Company, 1980). The Munsell colour system also does not have different measuring conditions for different measuring

environments. For example when measuring soil colour in the field under poor weather and lighting conditions and also for measuring soil colour indoors with different lighting sources. These given guidelines and conditions given for the Munsell soil colour charts apply to all environments (field and laboratory).

Relevant guidelines given by the USDA:

According to the USDA, visually describing a soil colour includes recording the colour name, the Munsell notation, the moisture state and physical state of the soil sample, e.g. brown (10YR 5/3), dry, crushed and smoothed. The soil colour should be described both in the dry and moist state. The physical state of a soil includes terms such as: broken, rubbed, crushed or crushed and smoothed.

When making a dry soil colour determination the soil should be air-dried and to a point where the colour would not change with additional drying. When determining a soil colour in the moist state, the moisture content of the soil material should be at a stage where no additional moisture would change the colour. The soil should be moistened to the point just before it starts to glisten. This is because at higher moisture contents the reflectivity of water in soils will start to influence colour determinations (Soil Survey Staff, 1975).

Factors that influence visual soil colour measurements in the field as ascribed by the USDA:

- The quality and intensity of the light reflected, together with the water content and surface roughness of the soil sample directly influences the light reflected by the human eye and how the colour of the soil will be perceived.
- Inaccurate colour measurements are predominantly made early in the morning and late in the evening (Soil Survey Staff, 1975).
- Just before sunrise and sunset, the light reflected by the sample and the colour chip may cause the hue reading to be one or two intervals redder than it would be if the reading was made at midday. This phenomenon can also be observed when the atmosphere is filled with dust and smoke particles.
- Soil colour would also appear different on overcast days when sunlight is more subdued than it would be in bright sunlight conditions.
- Because the roughness of a soil sample affects the light being reflected from it, care should be taken to assure that the resulting incidental light are as near as possible to right angles.
- When recording soil colour in the field, the measurements made should be reproducible by a number of individuals within 2.5 units of hue and 1 unit of value and

chroma. Notations should also be made to the nearest whole unit of value and chroma (Soil Survey Staff, 1975).

From the two guidelines discussed above, it is clear that errors will be made during visual field colour measurements. The guidelines given by the USDA seems to be more clear on what conditions need to be met for a colour to be assigned to a soil sample. The USDA also requires the observer to report the physical and moisture state of a soil sample, which is not the case with the Munsell soil colour chart guide. In terms of lighting conditions Melville and Atkinson (1985) states that visually matching soil colours cannot be achieved when the soil sample and the colour charts are being shaded from direct sunlight. This is because the light being reflected from the soil surface onto the back of the colour charts varies and will cause inaccurate matches. Measurements made under trees, will also cause inaccurate matches, because light are being randomly scattered from the leaves. According to The Soil Survey Staff (1975), the precision to which a soil colour can be determined in the field is limited to half of an interval between adjacent colour chips of the Munsell soil colour charts. To ensure relative precision in which a colour notation can be determined, it may be necessary for the observer to make use of all three guidelines. The length of the colour descriptions should also then be adjusted according to the purpose of the colour measurements.

2.2.1.2 Laboratory visual colour measurement conditions

According to Barrett (2002) precise visual soil colour measurement can only be achieved in the laboratory when using an appropriate viewing booth with a standard light source. Careful preparation of soil samples and a complete set of Munsell colour charts is also required. Most visual colour measurements made in the laboratory are based on the viewing and lighting conditions prescribed by the CIE in 1931. Both the Munsell soil colour charts and USDA make use of these standard conditions.

Relevant laboratory guidelines given by the CIE:

- The individual measuring the soil sample colour should have the ability to perceive all colours falling within the 400-700 nm spectral range. This person is then said to have normal colour vision and qualifies as a CIE Standard Observer.
- Because the colour perceived by the human eye changes according to the angle of view or the size of the object (soil sample) the CIE defined a 2° and 10° Standard Observer. The 2° field of vision represents a circle of nearly 15 mm at a viewing

distance of 450 mm, where the 10° field of vision corresponds to a circle of approximately 80 mm at the same viewing distance (Atkinson & Melville, 1985).

- The standard light sources prescribed by the CIE which is recommended for visual soil colour measurements is the CIE Source C and Standard Illuminant D₆₅.
- The light source should be placed at a 45° angle with the horizontal and the line of observation should be normal to the surface of the soil sample.

Other important factors to take note of when visually measuring soil colour in the laboratory and field is the use of viewing masks provided by the Munsell soil colour charts, correct sample preparation and the moisture content of the soil sample. The viewing holes in the Munsell soil colour charts have a diameter of approximately 10 mm and the viewing windows of the masks provided are 30 x 40 mm. This assures that reasonable approximations can be made with the CIE 2° Standard Observer conditions when measuring soil colour. The use of masks will also help standardize the dimension of the field of view and minimize problems related to colour contrasts (Atkinson & Melville, 1985). Because the CIE 10° Standard Observer allows a wider field of view, and obtains better average visual assessment matches, colour measurements determined with an instrument should preferably only be compared to this specific Standard Observer's visual measurements if the Munsell viewing masks were not being used. This means that viewing masks should always be used in visual measurements when following the 2° Standard Observer's conditions, that could then be compared with measurements made with the colour measuring instrument.

The physical state of a soil has an influence on how people would perceive the colour of that soil. Currently, no standard method or set of conditions have been adopted for the physical state of the soil when measuring its colour, whether it be visually or with instrument. In South Africa, Turner (1991) states in the ARC's "A Procedure for Describing Soil Profiles" that colour measurements made in the field should be on "unrubbed" soil samples. Also the only guideline for sample preparation in the field and laboratory given by the USDA is that the method used or the physical state of the sample should be clearly documented and kept constant throughout a study (Schoeneberger et. al., 2012).

A range of estimates can be recorded for Munsell hue, value and chroma when visual measurements are made by a number of different observers in the field and laboratory. To overcome these range errors, it was proposed to make use of appropriate instruments to measure soil colour (Atkinson & Melville, 1985). This requires the soil samples to be milled and air dried, which in the field will not be ideal for pedological studies. Unfortunately, the information that certain soil features expresses about a soil, for example, mottling, would be

removed during the milling process and will prevent variability between sampled soils. This will also then cause minimal characterization over a range of soil samples. Milling a soil affects its surface roughness. The surface roughness of a soil sample will affect the amount of light being reflected from that soil's surface. A study done by Sanchez-Marañón et al. (2011) and Gunal et al. (2008) shows that the colour of air dried undisturbed soil aggregates and the colour of air dried ground soil samples differs considerably in terms of lightness (CIE L* or Munsell value). The amount of time soil samples are being milled also affects the colour. The longer the sample is milled the lighter the colour of the sample will become (Barron and Torrent, 1993).

2.2.1.3 Effect of moisture on soil colour

The water content of a soil will also affect the lightness component (CIE L* or Munsell value) of that soil. With an increase in water content there will be a decrease in soil lightness, which is due to the decrease of reflectance from the soil surface (Barron & Torrent, 1993). Measuring a soil's moist colour in the field can cause concern since the moisture content of the soil can vary on a daily basis and may even vary on the same day. As mentioned, the USDA (Soil Survey Staff, 1975) thus made it a common practice to visually measure moderately moist soil samples when needed. Some researchers also made the choice that visual colour measurements in the laboratory should only be on air dried soil samples (Barrett, 2002).

2.2.2 Colour difference, colour space conversions and colour appearance

Euclidean distances can be used as a measure for calculating perceived colour differences within a uniform colour space. Euclidean distance can be defined as the physical distance between any two points or vectors contained within a three dimensional space (Atkinson & Melville, 1985). Both the Munsell colour system and CIE system have defined equations for describing colour differences based on Euclidean distance geometry.

The Euclidean distance measured between two Munsell colour chips was the first attempt to appropriately measure the numerical difference between perceived colours. This colour difference formula was developed on the assumption that Munsell value and chroma are equivalent in terms of their scale. According to Atkinson & Melville (1985), colour measurements performed by Godlove (1951) and the Optical Society of America (Judd & Nickerson, 1975) have found that in terms of perceived colour differences that one unit step of Munsell value was approximately equal to four unit steps of Munsell chroma. Calculating colour differences with the equation defined by the Munsell colour system, also known as ΔE ,

has shown that two adjacent colour chips respectively having low chroma but similar values, will have a small colour difference. Whereas two adjacent colour chips respectively having high chroma and similar value will have a greater colour difference (Atkinson & Melville, 1985). This means a greater colour difference (ΔE) is needed before a colour difference can be perceived between two adjacent colour chips having high chroma and similar value. An explanation for this, is because Munsell chroma is based on a numerical scale, where zero chroma represents neutral grey colours and a maximum of twenty where a colour is at its most vivid. Visually this means that humans are able to distinguish in some cases more easily between less vivid colours (low chroma) than more vivid colours (high chroma), because the ΔE value between the two colours become smaller as the two colours become perceptually darker or less vivid or colourful. The smaller the ΔE value, the easier it will be for humans to detect a colour difference.

The CIE $L^*a^*b^*$ colour space model also has a colour difference formula associated with it. ΔE^*ab is used to calculate the geometric (Euclidean) distance between two colour samples represented as points or coordinates in this three dimensional colour space. The geometric distance between two colour samples is then the colour difference between them. However not all colour difference formulae have an associated colour space. Many colour difference formulae were developed by modifying existing colour spaces (Luo, 2002). In colorant and lighting industries the access of different colour difference formulae created inconsistencies, which forced the CIE (Luo et. al., 2001) to develop the CIEDE2000 colour difference formula. This formula is developed from numerous modifications made to the CIE $L^*a^*b^*$ space model and is currently used as the standard colour difference formula across all industries (Luo, 2006). Regardless of these developments, ΔE^*ab is still the most widely applied colour difference formula. ΔE^*ab also presents some complications. As discussed in section 2.1.2.2 the colour discrimination threshold of the human eye greatly differs from the colour differences defined by the CIE $L^*a^*b^*$ colour space model. Research conducted by Luo et. al. (2001) explains the ability of the human eye to differentiate between colours. From their results they also concluded that the human eye finds it difficult to differentiate between colours with high chroma. Humans also struggle to perceive colour differences between hues with same values and chroma. This also applies for colour differences in terms of lightness. An L^* value of 50 is considered to be where the eye is most sensitive for colour difference recognition, and will decrease with higher or lower lightness (Luo, 2002). As mentioned in section 2.1.2.2, L^* indicates the lightness of an object that ranges from zero (black) to hundred (white), with a value of 50 being in the middle of this lightness scale.

Luo et. al., (2001) also found that for the colours located in the blue region of the CIE colour space the direction of colour difference recognition changes. This means that the change in saturation or chroma for blue colours do not increase gradually from the centre of the colour space, outwards, but are skewed to the left (Figure 2.7) when it comes to colour difference recognition. The ellipses shown in Figure 2.7, also called MacAdam Ellipses, represents the colour discrimination threshold of the human eye in terms of saturation and hue. This means that the colours occurring within the same ellipse cannot be differentiated by the human eye.

Figure 2.7 is called a CIE xy chromaticity diagram (Luo et. al., 2001). This diagram was constructed from the CIE Yxy colour space model that was defined in 1931. Because the non-linear CIE XYZ colour space model was not ideal for visually illustrating a colour, the CIE Yxy colour space model was created and used to illustrate colour in a two dimensions independent of lightness (Y). Y is identical to the tristimulus value Y from the CIE XYZ colour space model, and x and y are the chromaticity coordinates calculated from the X and Z tristimulus values (Rossel-Viscarra et. al., 2006).

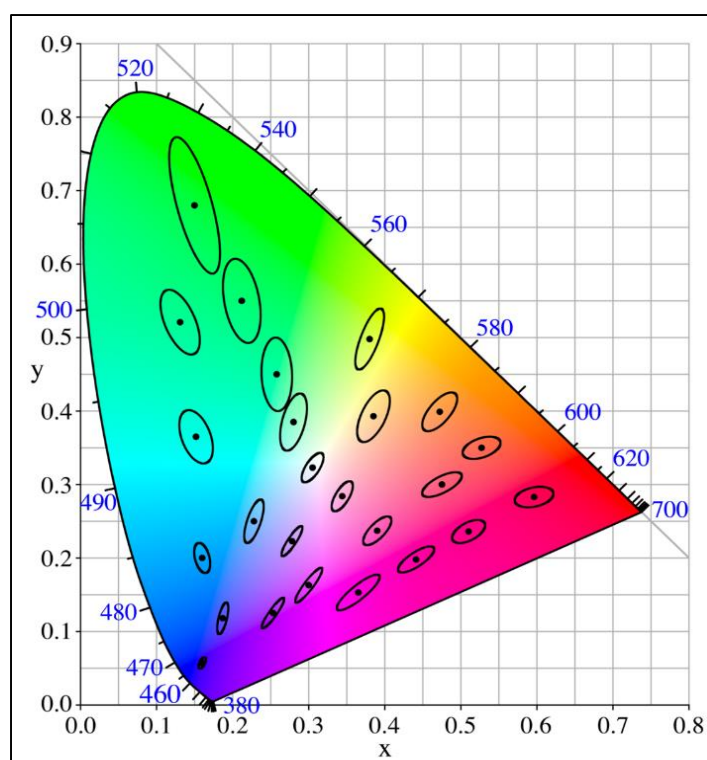


Figure 2.7: CIE x, y Chromaticity Diagram (Commons, 2015).

Soil colour differences are applicable to many aspects of soil science. For example, in remote sensing there is an increased interest in the spatial variation of surface soil colour. Soil

processes that affect surface soils can also be identified by colour differences enabling us to categorize, evaluate and map soils (Rossel-Viscarra et. al., 2006). The way colour data is recorded and communicated in both the preceding examples differ. In remote sensing the colour data would be recorded with the specifications of the RGB system, whereas, recording of surface soil colour in relation to pedological processes can be made with the Munsell system or the CIE system. Based on the nature and purpose of a study it may become necessary to convert colour data from one colour system to another. The geometry of the Munsell colour system and that of the CIE system are not the same, which makes it challenging to simply convert from one colour space to another. However, the transition between the Munsell colour space and that of the CIE system can be achieved instrumentally measuring the reflectance curve of each colour chip, obtaining the tristimulus values XYZ of each (Escadafal et. al., 1988). These tristimulus values can be converted to CIE $L^*a^*b^*$ values with definitions defined by the CIE in 1976. These corresponding $L^*a^*b^*$ values, now available in the form of tables and graphs, can be used for the conversion of Munsell notations. Specialized computer programs are also being used to achieve these conversions (Barron & Torrent, 1993). RGB values can also then be deduced when the light under which the charts are observed are accounted for during calculations. A set of tables containing these RGB values has already been published by Wyszecki and Stiles (2000).

CIE XYZ tristimulus values serves as the platform from where various other colour space transformations can take place from. Different and specific equations, algorithms and computer programs exist to accomplish these transformations including back transformations between the CIE XYZ, Munsell hue, value, chroma, CIE $L^*a^*b^*$ and RGB colour systems (Rossel-Viscarra et. al., 2006). The best colour model for the description of colour depends on the purpose of a study. When soil colour is only being used for descriptive purposes the Munsell system would be sufficient, but when it is being used for quantitative, numerical or predictive analysis the other space models discussed would be more appropriate (Rossel-Viscarra et. al., 2006).

Although the colour of two soils or the colour of a soil and Munsell colour chip may have identical CIE tristimulus values, there is always a possibility for them not to match when visually compared under different light sources, which led to the development of colour appearance models (Luo, 2006). CIECAM02 is a colour appearance model that evaluates the influence of different lighting conditions on perceived colour (Sánchez-Marañón et. al., 2011). This appearance model also contains a uniform colour space that can be used to evaluate small and large colour differences. The advantage of such an appearance model is that it enables us to predict what a colour will look like when viewed by a standard observer in a variety of lighting conditions (Ford & Roberts, 1998).

In terms of soil colour measurement, this appearance model was used in a study by Sánchez-Marañón et. al. (2011). In this study they investigated the influence of natural sunlight on soil colour descriptions using Munsell soil colour charts. The objectives of the study was to compute the colour appearance of the soil samples and Munsell colour chips under different daylight conditions to evaluate any colour changes, and also to calculate the colour differences between soil samples and Munsell colour chips. What they found was that a difference in daylight conditions reddened or yellowed the soils and Munsell colour chips according to their individual reflectance spectral properties. An overall increase in soil sample hue was observed and also a slight decrease in the samples lightness and chromaticity (Sánchez-Marañón et. al., 2011). From sunrise to sunset the hue of 79% of the soil samples varied between one and four Munsell colour charts, 2.5 to 10 units of hue redder or yellower depending on the day and hour. The variation in hue increased when the chroma of the soil decreased (Sánchez-Marañón et. al., 2011). They also found that when the solar elevation is greater ($>$) than 9° the possibility of having more than one Munsell colour chip matching the soil is reduced by 19%. This means that measuring soil colour during mid-day hours will result in more accurate soil-colour chip matches. When the colour notations of the soil samples measured at mid-day in the field was compared to colour measurements performed under laboratory conditions they found that a third of the field measurements did not match that of the laboratory measurements (Sánchez-Marañón et. al., 2011). Using this appearance model they concluded that visual field colour measurements are only a preliminary approach and accurate visual colour measuring conditions can only be achieved through instrumental measurements under controlled lighting (CIE Source C) in the laboratory. Or if a visual soil-colour chip matching technique is used in the laboratory, the use of a colour cabinet and Standard CIE Source C or D_{65} lighting is encouraged (Sánchez-Marañón et. al., 2011).

2.2.3 Colour measuring instruments

To exclude errors made with visual soil colour measurements a more objective approach to colour measurement is preferred. Three types of instruments can be used to generate objective colour measurements. These include spectroradiometers, tristimulus colorimeters and spectrophotometers (Barrett, 2002).

Errors in visual colour measurements can occur when uncontrollable changes occur in terms of viewing conditions. The use of an instrument can reduce these errors considerably since measurements can be made in a controlled environment. Despite the advantages of using instruments over visual methods for colour matching, there are shortcomings with the use of instrumental data. These problems include: the difficulty of comparing instrumental data with

visual data, the fact that many instruments can only be used in a laboratory environment and not be taken into the field, the lack of access to these instruments and the expenses required to obtain them and also the satisfaction of using traditional visual matching methods (Barrett, 2002). Traditional visual colour matching may be satisfactory, in part because some soils may not require precision and repeatability for its application beyond what is achievable with visual matching. Fortunately portable versions of these instruments are becoming available, so that field use will become more achievable (Barrett, 2002). Soil applications that can benefit from more precise and repeatable measurements not achieved by visual matching, has led to the development of methodologies (USDA) for effective instrumental use and the establishment of to what extent instrument-derived data are comparable to previous visual estimates. As mentioned, spectrophotometers, tristimulus colorimeters and spectroradiometers are three types of instruments used for measuring colour. These instruments are also appropriate for soil colour measurements.

Spectrophotometers records measurements across the energy spectrum and compares the ratio between the reflected light leaving an object and the calibrated working standard of the instrument (Barrett, 2002). These ratios are dimensionless quantities that are used for the colour measurement of surface colours. Spectrophotometers also contain a standard light source that standardize measurements when ambient light is not sufficient (Barrett, 2002). The samples are placed in direct contact with the spectrophotometer. The greatest advantage of the spectrophotometer is that they are very versatile. They are also able to detect metamerism and readings can be recorded as spectra or converted to different colour measurement systems with a variety of illuminant/observer combinations (Zwinkels, 1996).

Tristimulus colorimeters imitates the spectral response of a particular CIE standard observer combination by using three filtered photodetectors, red, green and blue that contains its own standard light source (Wyszecki & Stiles, 2000). Measurements are made through direct contact between the sample and the instrument. Results are recorded as one or more standard colour coordinate system, but cannot report any information on the underlying spectral data (Zwinkels, 1996). The advantages of colorimeters is their speed, ease of operation and good measurement repeatability. This makes the instrument very useful in the field and laboratory, particularly for visual colour difference evaluations. The main disadvantages of these instruments is the fact that they cannot detect metamerism and also the limited information given for a particular illuminant/observer combination (Zwinkels, 1996).

Spectroradiometers measure radiometric quantities using narrow wavelength bands across the energy spectrum (Barrett, 2002). These instruments are dependent on the immediate surrounding light conditions and is used to measure the reflectance at some distance from a

sample, as is the case for remote sensing applications. It can also be used to measure the colour of self-luminous samples such as pure quartz sand. A spectroradiometer's field of view is usually larger than that of colorimeters and spectrophotometers and the results are reported as the ratio between the reflection of the sample and a uniformly white surface contained within the instrument (Barrett, 2002). The results can be reported as spectra or be converted into a variety of colour measurement systems. A disadvantage of this instrument is that uncertainties are caused between inter-instrument comparisons, due to the lack of a standard illuminant and viewing geometry (Zwinkels, 1996).

2.2.4 Sensory data analysis

Visual soil colour measurement is a sensory analysis which is defined as:

“The identification, scientific measurement, analysis and interpretation of the properties (attributes) of a product as they are perceived through the five senses of sight, smell, taste, touch, and hearing” (Carpenter et. al., 2000).

Sensory analysis involves the removal or control over sources that causes unwanted errors. This is achieved by controlling the environment and sampling through a well-constructed experimental design and selecting the most appropriate individuals to make the measurements. It is also formulating the right objectives and taking the concept of human perception into account. Sensory data can be analysed by appropriate statistical methods that is determined by the nature of the objectives and the type of scale to be used (nominal, ordinal, interval, ratio scales) (Carpenter et. al., 2000).

When trying to establish how soil colour relates to various soil chemical and physical parameters numerous difficulties can be encountered. Firstly, colour measurement is subjective, secondly, soil colour cannot be described by one measurable parameter and thirdly, the expression of a particular soil colour is an amalgamation of various physical and chemical properties. From this perspective many parallels can be drawn with food science, where a particular taste or aroma is linked to a specific compound or combination of compounds. Fortunately a number of statistical tools are available, which aid the interpretation of sensory data. These methods have also been used in the field of food science (Baldwin et. al. (1998); Horsfield & Taylor (1976); O'Sullivan et. al. (2003)) and provide a useful starting point when dealing with soil colour data. The statistical methods that are used for sensory data analysis provide different types of data outputs in different formats. The following statistical methods are available to meet possible sensory objectives: exploratory visual methods (e.g.

histograms), univariate methods (analysing one variable at a time), multivariate methods (analysing several variables at a time), parametric methods (data is normally distributed) and non-parametric methods (data is distribution free).

Multivariate methods are some of the most frequently used methods of sensory data analysis. Of these multivariate techniques Principle Component Analysis (PCA) is a popular and ideal tool for soil and food scientists to analyse large correlated multivariate data sets (Webster, 2001). Multivariate methods can analyse a whole data set instead of individual elements and can also take into account a number of factors at the same time. The multivariate method can describe the relationships of colour pigments in a soil and factors that might influence it more precisely than univariate methods (Borůvka et. al., 2005). Principle Component Analysis are used to extract the most important information from a data set. This is achieved by compressing the data set to only the relevant data simplifying its descriptions and analysing the structure of the observations and the variables (Abdi and Williams, 2010). Studies on soil colour that have made use of PCA's include those by Melville & Atkinson (1985) and Sánchez-Marañón et. al. (2011).

Other methods that have been used in soil colour research includes, simple linear regressions (Barret (2002); Gunal et. al. (2008)), multiple linear regressions (Rossel-Viscarra et. al. (2006); Balasch et. al. (2013); Knicker et. al. (2004)), analysis of variances (Balash et. al. (2013); Knicker et. al. (2004); Sánchez-Marañón et. al. (1997)). Correlation coefficients (Knicker et. al. (2004); Torrent et. al. (1983); Gunal et. al. (2008) and factor analysis (Sánchez-Marañón et.al. (1997) which is another multivariate method which identifies underlying factors responsible for any correlation among variables (Borůvka et. al., 2005).

One of the major problems in colour analyses is the fact that at least three variables are needed to define a specific colour. This makes correlation of a single property with a soil colour challenging. Although the multifactorial analysis is usually used for such practices, some researchers have made an attempt to quantify colour or colour components using various techniques.

Studies that had been conducted to determine correlations between various soil parameters and separate colour components or variables include those of Yang et. al. (2001) who correlated soil humidity and soil surface roughness to CIE L*, a*, b* values, respectively. Barrett (2002) also performed a similar experiment where Munsell hue, value and chroma and CIELAB coordinates were respectively correlated to soil moisture and soil surface roughness. Another study by Burras et. al. (2003) investigated the correlation between soil organic carbon and Munsell hue, value and chroma. Sánchez-Marañón et. al. (2004) used CIELAB coordinates respectively and correlated them to aggregated and dispersed soil

samples, also for sand, silt and clay samples before and after sequential removal of organic matter (OM), carbonates (CO₃) and Fe oxides. In the same study Sánchez-Marañón et. al. (2004) used the ΔE^*ab value between the aggregated and dispersed soil to calculate its correlation to the previously mentioned soil parameters and properties. Atkinson & Melville (1985) discussed a method of colour difference designation that was established by Godlove (1951). This method is based on the Euclidean distance between a Munsell reference colour and a visually measured Munsell colour. In this regard Munsell notation differences could now be quantified into a single value. In studies where all three colour variables or components are used together to form correlations are those by Torrent et. al. (1983). In this study they developed redness indices that allowed them to estimate the hematite contents in soil. The two empirical based indices, redness rating (RR) and redness index (RI) are based on the Munsell notation and the CIE chromaticity coordinates (Y, x, y), respectively. Other studies by Torrent & Barron (2003), (1986), Sancho et. al. (2005), Peterschmitt et. al. (1996) and Brouwer & Fitzpatrick (2002) all made use of the redness rating index in their research. These two indices can only be applied to soils having a hue of 7.5YR and redder. Another theory developed from combining colour variables is the Kubelka-Munk theory. This theory can be used to predict the colour of a soil that consists of a mixture of different minerals and materials, each possessing its own set of spectral properties. Other studies that made use of this theory includes those by Sánchez-Marañón et. al. (2004); Barrón & Torrent (1993) and Barrón & Torrent (2003).

2.3 Factors influencing soil colour

The colour of a soil is one of the most obvious characteristics recognised by pedologists and soil surveyors. The slightest difference in colour of one soil horizon in a profile can be significant when having to classify a soil into one of various groups (Pendleton & Nickerson, 1951). With changing theories of soil genesis and advances in soil classification, the significance of colour used in the criteria for differentiating among soils has increased. Up until the early 1950's no clear conclusions could be made about the factors responsible for soil colour. This is because indirect methods, such as removing specific physiochemical properties from soils were used to assess the colour (Murti & Satyanarayana, 1971). An example of this would be when Fe and soil organic matter (SOM) is individually removed from a red soil via laboratory methods from where conclusions can be made about which property is responsible for red colour in soils. Soil colours recorded during field surveys also caused misperceptions since different methods were used for colour descriptions that produced very subjective results. Recognizing the lack of standard colour measurement procedures, Pendleton and

Nickerson (1951) proposed a universal methodology in specifying soil colour, and recommended that the Munsell colour charts should be used for all soil colour recordings. Using the Munsell colour charts, together with the data of possible factors affecting soil colour, researchers could now determine how soil colour will be influenced in terms of Munsell hue, value and chroma (Murti & Satyanarayana, 1971).

Soil colour is commonly associated with the relative proportions of three components, namely: SOM, Fe oxides and soil texture. Other constituents such as manganese (Mn) and calcium carbonate (CaCO_3) are also major variables that influence soil colour. When these colouring pigments are absent or removed, soils tend to have a greyish or bleached appearance. Due to the non-calcareous nature of the soils studied in the current investigation, the effect of CaCO_3 on soil colour will not be discussed at great length.

2.3.1 Organic matter as soil pigmenting agent

Dark coloured soils have long been associated with SOM content. This can be confirmed by the large body of literature available on this subject. Unfortunately early literature is limited in its usefulness because standard procedures for describing soil colour was not yet established (Schulze et. al., 1993). Only after the 1951 publication of the Soil Survey Manual (Soil Survey Staff, 1951) did soil colour descriptions greatly improve. This allowed numerous researchers to develop correlations between OM content and soil colour. Value and chroma were identified as important components for the estimation of SOM using the Munsell colour system (Spielvogel et. al., 2004).

Steinhardt and Franzmeier (1979) who studied different techniques of quantifying SOM content in silt loam soils from Indiana, reported that SOM content had a good correlation with Munsell value and chroma, 90% of the time. Correlations were made on soil groups based on SOM content (< 3%, 3 – 5% and > 5%) and Munsell colour components. Similarly, the correlation between SOM and dry cultivated topsoil colour from Iowa were also studied by Konen et. al., (2003). They reported Munsell chroma and value to be good predictors of OC concentrations, showing r^2 values of 0.77 and 0.74, respectively. Shields et. al. (1968) obtained similar results for the colour of topsoils from podzolic profiles, reporting an increase in SOM with decreasing Munsell value. Murti and Satyanarayana (1971) who studied the colour of reddish-brown soils in India, also reported a moderately good correlation between SOM and Munsell value ($r = - 0.52$). Alternatively the colour of soils from the semi-arid regions of Spain was studied by Ibáñez-Asensio et. al. (2013) who reported weak correlations between OC content and Munsell hue, value and chroma. The weak correlations were attributed to the masking effect of other soil variables. According to Schulze et. al. (1993), visual colour

measurements are a major limitation when developing correlations between soil colour and SOM content or any soil chemical parameter affecting Munsell value for that fact. This is because the range of colours produced by differences in specifically OM is actually small. When OM differences can produce prominent differences in the colour of soils, the actual differences in Munsell value may only be two or three units (Schulze et. al., 1993). The use of a spectrophotometer allows for more differentiated soil colour measurements. These measurements are also more accurate and precise when compared to visually measured soil colours. Studies that expressed spectroscopic data in CIELAB colour space systems include: Spielvogel et. al. (2004); Sánchez-Marañón et. al. (2004); Sánchez-Marañón et. al. (1997); Yang et. al. (2001) and Schulze et. al. (1993).

In terms of the CIE $L^* a^* b^*$ system, Spielvogel et. al. (2004) reported a r^2 value of - 0.38 for the relationship between SOM and soil lightness (L^*) of different soil types located in southern Germany. They attributed the weak negative correlation to the texture of the soils and the large heterogeneity of the study area. Similarly, research by Yang et. al. (2001), on the effects of climate on different soils from China, reported that the %OC have a strong negative correlation ($r^2 = - 0.88$) with L^* . Sánchez-Marañón et. al. (1997) used the CIE $L^* C^*_{ab} h_{ab}$ system to determine the relationship between %OC and red soil colour located in the Mediterranean. The L^* , C^*_{ab} and h_{ab} components represent Munsell hue (h_{ab}), value (L^*) and chroma (C^*_{ab}), respectively. From the results they reported SOM being negatively correlated with L^* and a strong negative correlation with C^*_{ab} . Sánchez-Marañón et. al. (2004) conducted a similar study where soils of various colour, located in southern Spain, were correlated with SOM. They also reported SOM to have a negative relationship with L^* and a strong negative relationship with C^*_{ab} . For each 1% of OC it reduced the soil lightness by 4% and chroma by 14%.

Due to the compositional heterogeneity of SOM, the general relationships between OM content and soils colour may be complicated (Spielvogel et. al., 2004). According to Schulze et. al. (1993) extractable OM can usually be subdivided into two fractions based on their solubility. This includes humic acid, which is dark in colour and fulvic acid, a light coloured material that may contain yellow or red pigments when in solution. Micheli et. al. (1989) and Schulze et. al. (1993) found a correlation between the amount of fulvic acid, humic acid and Munsell value after they subjected SOM to chemical fractionation. Black humic acid being the major pigment in both studies. When a soils fulvic acid concentration is higher than the humic acid concentration, the soil will appear lighter in terms of Munsell value. This was the case for a study conducted by Shields et. al. (1968) on celcic and podzolic soils in Canada. From the results they reported that celcic soils had slightly lower Munsell values than podzolic soils

despite both soils having the same carbon content. They concluded that the difference in lightness could be attributed to the nature of the OM in these soils.

When research is being conducted on soils from a large geographical area, the prediction of soil properties such as SOM or %OC from colour data becomes difficult, since the nature and properties will differ from one place to another (Konen et. al., 2003). Unique relationships thus exist for different soil landscapes.

2.3.2 Iron oxides as soil pigmenting agent

The Fe oxide content of soils also has an influence on soil colour. During aerobic weathering Fe^{2+} is oxidised to Fe^{3+} from where it is hydrolysed to form Fe oxides (Schwertmann, 1993). Iron oxides that occur in aerobic soils are immobile and have low solubilities. They also express prominent colours ranging from yellow to red, particularly in the lower parts of soil profiles where black SOM is not masking these striking colours (Sánchez-Marañón et. al., 2004). Iron oxides predominantly form from Fe containing parent materials, thus reflecting the homogeneous (original) Fe distribution of the parent rock. Iron oxides can also be solubilized by bacterial respiration in anaerobic conditions, forming mobile Fe^{2+} that relocates itself in aerobic zones. In these zones the heterogeneous distribution of ferrous Fe is reoxidized to form new oxides and different colours (Schwertmann, 1993). The newly formed Fe oxides can again be remobilized by organic complexes that formed between Fe and organic ligands. This remobilization process is essential for podsolization to occur (Schwertmann, 1993). Iron oxides can also be absent from a soil horizon or portions of a horizon, giving the soil a greyish or whitish (bleached) appearance. The total or partial removal of Fe oxides supplies valuable information because it indicates that either little or no weathering or complete removal of Fe oxides took place through microbial reduction or chelation (Schwertmann, 1993). The processes involved with Fe reduction or chelation, includes: lessivage, ferrollysis and podzolization, which will be discussed further in Chapter 5.

The pigmentation of most aerobic soils is predominantly controlled by the type(s) of Fe oxides present and mainly effects the colour in terms of Munsell hue (Schwertmann, 1993). According to Soileau & McCracken (1967), Munsell chroma can also increase as the concentration of certain Fe oxides increase, given that Munsell hue stays constant or vary along a narrow range.

The Fe oxide, hematite is responsible for the red colour in soils and can be recognized by its 7.5R to 5YR hue (Schwertmann, 1993). Hematite can occur in a variety of soils, but is more prone to develop in soils from warm tropical regions. Low soil moisture activity (well-drained),

low SOM, high soil temperatures and parent materials high in total Fe are all factors contributing to the formation of hematite (Wheeler et. al., 1999). South Africa's current climate conditions are still conducive to hematite formation, although the occurrence of hematite in the Western Cape generally represents past tropical environments that favoured hematite formation. As mentioned in section 2.2.4, hematite content in soils can also be predicted from colour with the use of various redness indices such as the redness rating (RR) and redness index (RI) of Torrent et. al. (1983).

Another common form of Fe oxide in soils which generally co-exist with hematite, is goethite. Goethite is considered to form universally in soils irrespective of the climatic conditions. But its formations will be favoured as a result of pedogenic processes that occur in cool, wet and temperate regions. In the presence of OM, goethite formation will be favoured over hematite (Wheeler et. al., 1999). When goethite is the dominant Fe oxide in a soil, it can be recognized by its 10YR to 7.5YR hue (Schwertmann, 1993).

The colour of soils from the semi-arid regions of Spain was studied by Ibáñez-Asensio et. al. (2013). Although they reported that Fe oxide content had no significant effect on soil lightness (L^*), they did find a significant relationship between L^* and hue (h^*_{ab}), which may indicate the indirect effect of Fe oxides on soil lightness. From this relationship they found that red (hematite) soils were generally darker than yellow (goethite) soils. Sánchez-Marañón et. al. (2004) also conducted a study where soils of various colour, located in southern Spain, were correlated with soil properties such as Fe oxides. They reported that when Fe oxides are removed from soils the hue (h^*_{ab}) and value (L^*) significantly increases and chroma (C^*_{ab}) significantly decreases. Chroma being the main component responsible for the intensity of pigmentation in their study. Sánchez-Marañón et. al. (1997) reported from their study on the relationship between OC and red coloured soils located in the Mediterranean, that there is a direct relationship between hue and chroma, and value (lightness) and chroma. This is because the chroma tended to increase as the hue decreased (become redder) and the value increased as chroma increased. Hue and value accounted for 77% of the total variance in the colour population. Murti and Satyanarayana (1971) who studied the colour of reddish-brown soils in India, reported a very strong correlation between Munsell hue and ferrous Fe (Fe^{2+}) ($r = 0.83$), and a moderately strong correlations with ferric Fe (Fe^{3+}) ($r = - 0.57$). They concluded that the type of Fe oxide in soils is more important than any other soils characteristic when assessing the hue of the soils.

2.3.3 Significance of soil texture in terms of soil colour

From the numerous studies mentioned in the previous two sections, researchers came to the conclusion that OM and Fe oxide content in soils, alone, are not responsible for the colour of soils. What they found was that the effect of these properties will vary in different textured soils having diverse mineral compositions. According to Spielvogel et. al. (2004), soil lightness (L^*) is affected by soil texture because fine textured soils, consisting mainly of silt and clay particles, will reflect more light than coarse textured soils (sandy). Sand particles also have less specific surface area than clay or silt particles, which will allow less OM or Fe oxides to coat individual sand particles, resulting in a darker or redder/yellower soil (Gunal et. al., 2008). Research by Yang et. al. (2001), on the effects of climate on different soils from China, reported that coarse textured soils resulted in lower lightness (L^*) values than fine textured soils, which agrees with the statement above by Spielvogel et. al. (2004). Murti and Satyanarayana (1971) who studied the influence of soil chemical properties on the colour of reddish-brown soils in India also reported a highly significant negative correlation ($r = - 0.60$) between clay content of the soils and soil lightness (Munsell value). As the clay content increased in the soils the lightness component of the soils was negatively affected (became darker). The clay content of these reddish-brown soils also showed weak relationship with Munsell hue ($r = 0.05$) and chroma ($r = - 0.18$), meaning the soils tended to become more red and less colourful as the clay content of the soils increased. These relationships are the result of Fe content in the clay mineralogy. On the other hand, Ibáñez-Asensio et. al. (2013) found from their study on semi-arid soils from Spain, that clay content did not show any significant relationships to soil lightness ($r^2 = 0.04$). Both sand and clay fractions showed weak negative correlations with Munsell hue and weak positive correlations with chroma. The weak texture-lightness relationships obtained was due to studying the effect of texture on soil colour independently from the combined effects of Fe and organic matter on soil colour. Similarly Gunal et. al. (2004), reported from their research on the relationships between chromameter colour variables ($L^*a^*b^*$) and colour related soil variables on calcareous colluviums in northern Turkey, that clay content exhibited very weak correlations ($r = - 0.18$) with soil lightness (L^*). With an increase in the soils clay content the soils also became significantly more green in terms of a^* ($r = - 0.53$) and more blue in terms of b^* ($r = -0.60$). Concluding that soils become darker with an increased clay content that is due to the Fe contents of the clay minerals. The sand fraction of these reddish-brown soils showed very weak correlation with all three colour components (L^* , a^* and b^*) where the silt fraction showed good correlations with L^* , a^* and b^* .

Research by Konen et. al. (2003) on the relationship between soil texture and organic carbon content of cultivated topsoils in Iowa, reported that a high correlation ($r^2 = 0.71$) existed

between clay content and %OC concentrations in the soils. This means that with an increase in clay content the %OC concentrations also increased, affecting the lightness component of the soils (soil became darker). The opposite was observed for the sand fraction, where an increase in sand content caused a decrease in OC concentration. Thus a strong negative relationship ($r^2 = 0.74$) was observed between the sand content and OC concentrations in the soil. Spielvogel et. al. (2004) reported from their research on the relationship between SOM composition and soil lightness of different soil types located in southern Germany, that coarser textured soils are considerably darker ($r^2 = 0.63$) (lower L^* value) than fine textured soils ($r^2 = 0.85$) (higher L^* value) with similar OM contents. They explained these differences by the fact that sand consist mainly out of quartz, whereas silt and clay consist of a mixture of quartz, feldspar, mica and phyllosilicates having higher reflective properties. According to Schulze et. al. (1993), quartz crystals reflect light to a lower extent than other minerals found in the silt and clay fraction.

2.3.4 Other pigmenting agents

Previous research has also showed soil properties, other than SOM and Fe oxides, to have an effect on soil colour. These properties include Mn oxide and CaCO_3 content of soils.

Calcium carbonate content generally correlates to the lightness of soils. Soils high in CaCO_3 content being lighter in colour (Simonson, 1993). Even at low concentrations CaCO_3 will have a strong impact on the lightness of soils, unless Fe oxides and OM mask the effect of CaCO_3 . Spielvogel et. al. (2004), Sánchez-Marañón et. al. (1997) and Ibáñez-Asensio et. al. (2013) all reported from their studies that soil samples with higher carbonate contents had lighter colours. Gunal et. al. (2004), reported from their research on the relationships between chromameter colour variables ($L^*a^*b^*$) and colour related soil variables on calcareous colluviums in northern Turkey, that soil tended to become lighter with an increase in CaCO_3 . Calcium carbonate showed a stronger relationship with a^* ($r = 0.60$) than with b^* ($r = 0.38$) or L^* ($r = - 0.08$). The low correlation with L^* could be assigned to soils from various locations being studied as a whole instead of studying soils from each location separately.

According to Torrent et. al. (1983) the dark colour in soils are usually an indication of the OM content, however Mn may also be responsible for the dark pigmentation of soils. Manganese oxides are stable under conditions of high pH and high redox potential (Schwertmann, 1997). They are however present at a much lower concentration than Fe in most parent materials. When soils weather and acidify, Mn oxides become unstable, especially if OM is present. Murti and Satyanarayana (1971) who studied the colour of reddish-brown soils in India, reported that Munsell value decreased with an increase in Mn content ($r = - 0.39$).

2.4 The use of remote sensing techniques in determining soil colour.

Soil processes that affect surface soils may be identified by colour differences. This has led to surface soil colour being used to categorise, evaluate and map soils (Rossel et. al., 2006). Soil colour notation is usually achieved by comparison with Munsell Soil Colour Charts. This raw colour data is generally not relatable to soil spectral properties (Escadafal et. al., 1989).

In remote sensing of soil properties, effort has been made to convert Munsell notations into spectral reflectance data with the use of colorimetric equations (Escadafal et. al., 1989). Escadafal et. al. (1989) performed a study where they measured the spectral reflectance curves of 84 soil samples with a laboratory based spectrophotometer. The spectral data was converted into the RGB (Red, Green, Blue) notation using colorimetric equations. It was found that these RGB coordinate values were strongly correlated to the soil reflectance measured in the corresponding spectral bands of Landsat sensors. RGB coordinates were also determined from visual Munsell data using transformation programs and matrixes (Wyszecki & Stiles, 2000). Despite their low precision, these estimated colour coordinates were significantly correlated with the reflectance values of the Landsat sensors.

Similarly, a study conducted by Mathieu et. al. (1998) on the relationship between satellite-based radiometric indices and typical soil colour of arid environments, have shown that colour parameters can be directly computed from reflectance spectra using colorimetric equations. The colour data was expressed according to Helmholtz chromaticity coordinates containing two polar coordinates (λ_d - dominant wavelength and P_e - purity of excitation) and a luminance (Y) variable having a similar meaning to the Munsell hue, chroma, and value, respectively (Mathieu et. al., 1998). The Munsell system was also used to estimate soil colour. Linear regression analysis between soil colour and radiometric indices showed a systematic improvement of relationships from $r = 0.70$ for Munsell data to $r = 0.90$ using Helmholtz data. Thus simple radiometric indices (band combinations) calculated from broad blue (B), green (G), and red (R) bands are found to be good predictors of each of the soil colour components. Escadafal (1993) also used the transformation of Munsell data into Red, Green, Blue colour coordinates (R,G,B) as the basis for a practical, physically based model that relates surface colour to satellite data in visible spectral bands

Although not based on remote sensing, an alternative method for colour determination from digital data was performed by Van Huyssteen et. al. (2006). The study focused on the colour variation in digital photographs of ten soil profiles in the Weatherley catchment that was quantified and classified using a spatial analysis program. From the digital results they

reported topsoils to be predominantly grey (> 50 %), due to the darkening effect of humus in the A horizons. Generally grey colour also dominated E and G horizons (> 54 %) and in the unspecified materials with signs of wetness. Yellow-brown colours dominated in yellow-brown apedal B horizons, in upper soft plinthic B horizons, in neocutanic horizons and unspecified materials with signs of wetness underlying neocutanic subsoils. Red colour dominating in red apedal B horizons. They concluded that using this technology seems feasible to aid in the identification of E, yellow-brown apedal B and red apedal B horizons. The Munsell colour for each horizon was also calculated from corresponding R, G, B values obtained from the digital data. This produced weak correlations to visually determined Munsell colours. Hue contributed most to the lack of correspondence between the two procedures, which may be due to shortcomings that may have existed in the colour classification procedure and the colour correlation programme used.

From the review above it should now be clear that the colour of soils is heavily reliant on the way it is being measured. Thus in accordance with the objectives of this study, one needs to know how the various methods and conditions of soil colour measurement compare to each other, before one can determine if the colour of soils are bleached or non-bleached. It will also then be important to establish the chemical and physical controls possibly responsible for colour expression in soils.

CHAPTER 3

3. Materials and methods

3.1 Sample collection

3.1.1 Soil Profile database

The samples used for this investigation were sourced from the soil store at the ISCW. Sample selection was carried out using the following procedure: from the soil profile database of the ISCW all soils profiles containing red apedal B, yellow apedal B or neocutanic B horizons were selected (Avalon, Glencoe, Pindene, Griffin, Hutton, Oakleaf, Clovelly, and Bainsvlei soil forms). From these forms all soil series that showed the presence of free carbonates were discarded as they would classify as neocarbonate soil forms in the current classification system (Soil Classification Working Group, 1991). Majority of the soil series in the soil profile database were classified according to the first edition of the South African Soil Classification System (red book) that was published in 1977. Thus the soil series selected for this study had to be updated according to the changes made in the second edition of the South African Soil Classification System (Soil Classification Working Group, 1991). Of the remaining profiles, only those that had citrate bicarbonate dithionite (CBD) Fe analyses were selected for sample collection. A subsample of 5 g was collected from the A and upper B horizon from these profiles. The A and B horizons from 725 soil profiles were collected. The collected samples were transported back to the laboratory in Stellenbosch for detailed colour analysis. Table 3.1 lists the frequency of different soil forms requested from the database and Table 3.2 lists the frequency of different diagnostic subsoil horizons in these soil profiles.

The low occurrence (19 profiles) of neocutanic subsoils in the data set is not clear (Table 3.2). A possible reason might be that majority of the soils used in this study was classified using the previous edition of the current Soil Classification System (Soil Classification - A binomial system for South Africa, 1997). In the previous edition, soils containing neocutanic subsoils were not associated with any evidence of wetness. Situations where these soils might have shown evidence of wetness would then probably have been ignored or classified as another subsoil that would accommodate the wetness. If all the soils in the data set were to be classified with the current edition of the South African Soil Classification System (1991), there would be a great chance for more neocutanic soils to be identified, since evidence of wetness

in neocutanic soils are now being recognised in the new edition. These wet neocutanic soils now form part of the Tukulu soil form.

Table 3.1 Frequency of various soil forms occurring in the data requested from the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System.

Soil form	Frequency of occurrence
Avalon	86
Bainsvlei	21
Clovelly	122
Glencoe	15
Griffin	36
Hutton	414
Oakleaf	19
Pinedene	8

Table 3.2: Frequency of various diagnostic subsoil horizons occurring in the data requested from the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System.

Diagnostic Subsoil Horizon	Frequency of occurrence
Red Apedal	435
Yellow-Brown Apedal	267
Neocutanic	19

3.1.2 Study area

The distribution of the apedal and neocutanic subsoils collected for the study is shown in Figure 3.1. The highest density of neocutanic profiles being located in the Eastern Cape, Western Cape and Limpopo province. Kwazulu-Natal, Mpumalanga, Free State and Eastern Cape showing the highest density of yellow-brown apedal profiles. The red apedal profiles were wide spread across South Africa. From Table 3.3 it is clear that the density of the apedal soil profiles are not evenly distributed throughout South Africa. The highest density of soil profiles being located in the Eastern Cape and KwaZulu-Natal, with relatively few soil profiles located in the Western Cape and Guateng.

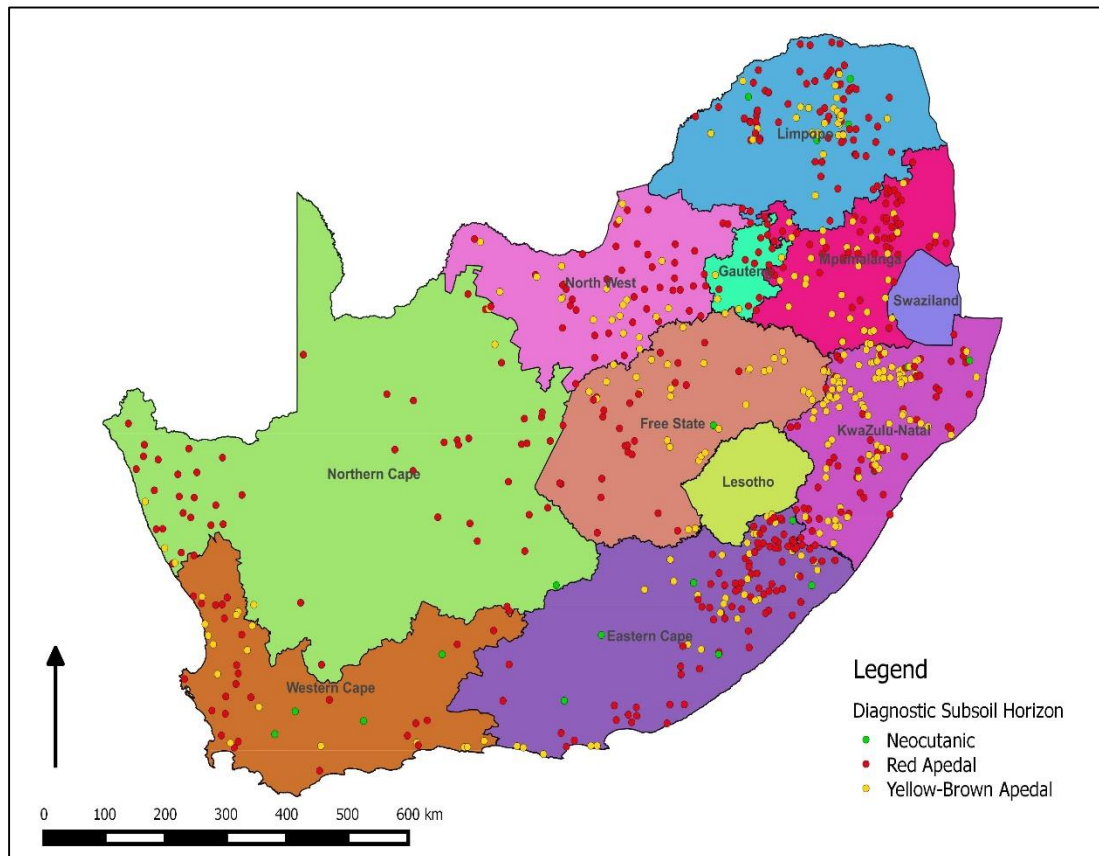


Figure 3.1: Spatial distribution of apedal and neocutanic subsoils selected from Land Type data for study.

Table 3.3: Frequency of selected apedal and neocutanic soil profiles occurring in each province of South-Africa.

Province	Frequency of soil profiles per province
KwaZulu-Natal	152
Eastern Cape	127
Limpopo	104
Mpumalanga	90
North West	67
Free State	62
Northern Cape	58
Western Cape	50
Gauteng	15

3.2 Laboratory procedures used for soil analysis in the Land Type Survey

The way soil samples were prepared for the Land Type Survey underwent a series of improvements and changes. According to personal communication with Dr Garry Patterson, senior soil scientist at the ARC, the method of soil crushing and sieving at the ARC-ISCW from 1972 to 1979 differs from the method currently used. As described by Sobczyk et. al. (1989), the two procedures are outlined below.

For the initial procedure, the soil samples were air-dried and placed in canvas sample bags and sent to the Soil and Irrigation Research Institute (SIRI) for analysis. Where necessary, the soil samples were further air-dried. For laboratory analysis a sufficient quantity of soil was machine crushed using a porcelain mortar and steel pestle (Nasco-Aspelin grinder), and sieved through a 1.68 mm mesh sieve. In the later procedure, soil samples were air-dried and a sufficient quantity was crushed by hand, using a porcelain mortar and pestle, before laboratory analysis. Crushed soils were then passed through a 2 mm sieve. The mass of all materials larger than 2 mm was recorded, and both the crushed and uncrushed soil was then sent to the SIRI for analysis and storage.

Full descriptions of the chemical, physical and geographical procedures and methods performed on the Land Type samples, are described in the South African Land Type Survey Memoirs (Sobczyk et. al., 1989). Table 3.4 provides a brief summary of the methods used.

All chemical, physical and geographical information for soil profiles analysed in the Land Type Survey and subsequent surveys and projects are digitally available in the Soil Information System contained at ARC-ISCW (Paterson et. al., 2014).

Table 3.4: Summary of the chemical and physical methods and procedures used in the analysis of the selective soil properties.

Soil Property	Method	Source
Organic Carbon	Walkley-Black Method (dichromate oxidation)	Allison, 1965
Extractable Aluminium (%)	200 cm ³ 0.3 M Na-citrate/1.0 M bicarbonate buffer solution + 10 g Na-dithionite (Atomic absorption) at 70°C	
pH H ₂ O	1:2.5 soil to water suspension	
CEC (meq/kg soil)*	150 cm ³ 0.5 M LiCl buffered at pH 8 with triethanolamine, extraction (Buchner funnel), washed with 150 cm ³ 80 % ethanol + 500 cm ³ 0.25 M Ca(NO ₃) ₂ , CEC (Amm.Acet.) Distillation and Titration	Modified version of Peech, 1965
Cation Na and Cation K (meq/kg soil)	150 cm ³ 0.5 M LiCl buffered at pH 8 with triethanolamine, extraction (Buchner funnel), 500 cm ³ leachate, or Amm.Acet. or LiCl exch.	Modified version of Peech, 1966; Longenecker and Lyerly, 1964
Cation Ca and Cation Mg (meq/kg soil)	150 cm ³ 0.5 M LiCl buffered at pH 8 with triethanolamine, extraction (Buchner funnel), 500 cm ³ leachate, Ca (flame emission), Mg (Colourimetrically), Amm.Acet. or LiCl exch.	Modified version of Peech, 1966; Longenecker and Lyerly, 1965; Horwitz, 1965
CBD Fe (%)	CBD (new) ¹ , CBD (old) ²	
Total Sand % (coSa, meSa, fiSa, vfiSa)	Dry sieving (particles < 2 mm, <1.68 mm [earlier samples])	Day, 1965
Total Silt and Total Clay %	Pipette and sedimentation (5 or 7 fractions)	Day, 1965
Modulus of rupture (kPa)	soils < 2 mm packed into rectangular moulds, saturated with de-ionized water ± 6 hours, dried at 45°C, increased forced applied on centre of soil briquette till failure occurred	Reeve, 1965
Dispersion ratio (%)**	20 g air-dry soil + 1 ℓ shaken 40 sec, concentration of <20 µm particles determined with pipette method.	Modified version of Willen, 1965

* 150cm³ 80% ethanol added in 3-4 portions, with complete drainage between portions

** (mass (g) <20µm particles / mass (g) silt + clay in sample) x 100

¹ Before the pretreatment of soil samples for mineralogical analysis and after particle size distribution were determined, the <2µm and 2 - 50µm fractions were collected in 250cm³ bottles. The clay fraction was saturated with 1M MgCl₂ and repeatedly shaken up with de-ionized water and centrifuged until chloride free (AgNO₃ tested) and freeze-dried. The 2-50µm fraction was dried overnight at 70°C. CBD Fe was determined separately on 1g samples with the method described above. These procedures were adopted from soil sample C5797.

² The old method of CBD Fe determination, as referred to in the Land Type database (before soil sample C5797) did not include the additional procedures as described in the new method above.

3.3 Colour measurement

The soil colours in the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System were predominantly made in the moist state, with few dry colours being recorded. Since colour analysis is central to the overall aim of this study, consistent colour assignment is essential. For this reason all sample colours were re-measured in both the moist and air-dried state under the lighting conditions described below. It is therefore important to note that all soil colours presented in this study are measured on crushed, sieved samples. Both visual and spectroscopic colour measurements were used in this study.

3.3.1 Spectrophotometer measurements

Colour measurements were made on all 1450 collected soil horizon samples using a hand-held Konica Minolta CM 600d spectrophotometer. This instrument has an internal xenon light source and $d_i:8^\circ/d_e:8^\circ$ geometry. It reports spectral reflectance from 400 to 700nm at 10nm increments, which it uses to calculate parameters in a variety of colour coordinate systems, including Munsell system, CIE $L^*a^*b^*$ and RGB (Barrett, 2002). All spectrophotometer measurements made for this study were performed using D65 standard illuminant and 10° standard observer viewing conditions. The viewing conditions were set using SpectraMagic NX software, which is colour data software designed to enable spectrophotometer measurements and graphical display of sample data. The instrument measures reflectance over an 8-mm-diameter circular area and is used with specular (gloss) component included (SCI). Measurements are standardised by calibration against a manufacturer-provided white plate of known reflectance, also called white calibration. The white plate is located on the inside of the white calibration cap with its calibration data stored in the internal memory of the instrument. Before a white calibration was performed a zero calibration was also performed using the optional Zero Calibration Box CM-A182. The integrating sphere of the spectrophotometer was protected by placing a pure quartz glass plate over the soil sample prior to its dry and moist state measurement. This quartz plate contains no reflective properties.

Colours measured by the spectrophotometer are reported in CIE $L^*a^*b^*$ notation. To ensure appropriate correlation to visual observations and to enable bleached colours to be recognised it was necessary to convert the L^* , a^* and b^* values to the closest hue, value and chroma of the Munsell system. This was done through spectroscopic measurements of the Munsell colour chips rather than direct conversions using mathematical formulas (Rossel-Viscarra et.

al., 2006). All 238 standard colour chips from a new copy of the Munsell soil colour charts (Munsell Color Company, 2000) (Charts 10R, 2.5YR, 5YR, 7.5YR, 10YR, 2.5Y and 5Y) were measured with the spectrophotometer. These colour chips were set as colour targets and all L^* , a^* and b^* values measured for the soil samples were assigned to the nearest Munsell chip target. The tolerance value for the Euclidean distance (ΔE^*_{ab}) for each target Munsell colour chip was set at six. The spectrophotometer also reported colour in Munsell notation that is based on continuous rather than discrete data as is the case for Munsell colour charts.

The soil colours were measured by placing a 5 g dry soil sample on white paper. A pure quartz glass plate was placed over the sample. Once the glass plate was levelled onto the sample, the measurement was taken directly on this glass surface. This measurement procedure was also repeated for the moist colour measurements. Soil samples were moistened with the same method used for moist visual colour measurements. The glass plate was cleaned after every measurement taken to prevent contamination. For each soil the L^* , a^* and b^* values were recorded as well as the colour of the nearest Munsell colour chip.

3.3.2 Visual colour measurements

A subset of 193 randomly selected soil samples were visually analysed for soil colour using a new Munsell soil colour chart (Munsell Color Company, 2000). Colour designations were made by a single observer in the laboratory under standard tabular fluorescent laboratory lighting (4000 K) as a D65 illuminant could not be sourced. Samples were measured next to a southern window in the laboratory. Natural light through windows was allowed, and direct sunlight with soil samples was avoided (Atkinson & Melville, 1985). Any reflective objects near the measuring bench that may have influenced the colour measurements were removed. Colour measurements were taken between 09:45 am and 16:30 pm on non-consecutive days. A 5 g soil sample was placed on white paper, from where the colour was assigned. The moist colour of each sample was determined directly after the determination of the dry soil colour by spraying the sample with de-ionized water until moist.

The weather conditions for each day visual colour measurements were made for the 193 soil samples, are given in Appendix 1, Table A1.1.

Dry visual colour estimates of 100, randomly selected, soil samples were also made in the laboratory as described above. The viewing masks included in the Munsell colour charts were used to facilitate the designation of soil sample colours. The dry soil colour was also visually measured and facilitated with the viewing masks, by placing a 5 g soil sample in direct sunlight.

Colour measurements for the 100 soil samples were taken between 10:30 am and 13:30 pm over a period of two consecutive days.

Visual colour measurements made for this study in outdoor conditions will be referred to as natural daylight measurements hereafter. Visual colour measurements made previously in the field during the Land Type Survey will be called field measurements. Visual colour measurements made in the laboratory will be referred to as laboratory measurements and those made with the spectrophotometer will be called spectroscopic measurements.

For soil applications where precision and repeatability of colour measurement is necessary, use of the spectrophotometer provides superior results to those visually matched with Munsell charts, and also eliminates the subjectivity of human vision (Barrett, 2002). Determining soil-colour relationships from a heterogeneous group of soils might produce weak correlations that may be improved by studying soils with similar characteristics or from similar geographical areas.

3.4 Lithological discontinuity testing

It has been suggested (Fey, 2010) that topsoil bleaching may be associated with soil profiles containing lithological discontinuities. Lithological discontinuities are generally identified within a soil profile by contrasts in the relative amounts of the various sand fractions. It has also been suggested that lithological discontinuities may be identified by contrasts in the mineralogical composition of the coarser texture fractions (Fey, 2010). Lithological discontinuity of the soil profiles used in this study were tested using two methods, namely the uniformity value (UV) (Cremeens & Mokma, 1986) and the cumulative particle size distribution (CPSD) (Langohr et al., 1976). Both methods compare the particle-size data of the upper horizon to that of the lower horizon.

To calculate the UV the following equation was used:

$$UV = \left[\frac{[(\% \text{ silt} + \% \text{ very fine sand}) / (\% \text{ sand} - \% \text{ very fine sand})] \text{ in upper horizon}}{[(\% \text{ silt} + \% \text{ very fine sand}) / (\% \text{ sand} - \% \text{ very fine sand})] \text{ in lower horizon}} \right] - 1$$

The closer the UV is to zero the higher the probability that the two horizons have the same parent material. A UV > 0.6 indicates that a lithological discontinuity is present in the soil profile (Cremeens & Mokma, 1986).

The CPSD index was calculated using the equation provided by Langohr et. al. (1976) as follows:

$$I = \sum_{i=1}^n m_i$$

Where I = CPSD index; n = number of fractions; and m_i = lowest percentage value in adjacent horizons of fraction i . The CPSD index is obtained by summing for each fraction the lowest value (m) observed in one of the samples (consecutive soil horizons).

For this study a more simplistic version of the equation provided by Langohr et. al. (1976) was used to calculate the CPSD %. Only sand fraction data were used for the calculations. To calculate the index for each soil profile of this study, the following equation was used:

$$\text{CPSD \%} = \text{MIN (coSa fraction)} + \text{MIN (meSa fraction)} + \text{MIN (fiSa fraction)} + \text{MIN (vfiSa fraction)}$$

where MIN = selecting the smallest fraction value from adjacent soil horizons occurring within a specific soil profile; coSa = coarse sand fraction; meSa = medium sand fraction; fiSa = fine sand fraction; and vfiSa = very fine sand fraction.

To determine if there was lithological uniformity in a soil profile Liebans (1999) subjectively chose to use a threshold value of 90%, where Rindfleisch and Scaetzi (2001) used a CPSD threshold value of 94%. For this study, three groups, based on CPSD % were selected to identify possible lithological discontinuities in the soil profiles. The groups were the same as those proposed by Delvigne et. al. (1979). He suggested soil profiles having a CPSD % >94 will be lithologically uniform, borderline uniform when they are between 94 – 90% and below 90% lithologically discontinuous.

3.5 Soil chemical and physical calculations

Other additional parameters that were calculated and added to the original data received from the ISCW include: sum of exchangeable cations (S - value), base status (eutrophic, mesotrophic, dystrophic), effective cation exchange capacity (ECEC), exchangeable Na % (ESP), exchangeable Mg % (EMP), and clay movement down the soil profile (luvic or non-luvic). Calculations were performed as specified by the South African Soil Classification Working Group (1991). The Fe oxide content of each soil was also estimated using a soil colour index (Barron and Torrent, 1986).

The total amount of exchangeable cations (S – value) in the soil were calculated with the following equation:

$$\begin{aligned} S - value &= \Sigma (K^+ + Na^+ + Ca^{2+} + Mg^{2+}) \\ &= \text{cmol}_c \text{ kg}^{-1} \text{ soil} \end{aligned}$$

To determine the base status of each soil sample, the following equation was used:

$$\begin{aligned} \text{Base status} &= \frac{(S - value \times 100)}{\text{Clay \%}} \\ &= \text{cmol}_c \text{ kg}^{-1} \text{ clay} \end{aligned}$$

(< 5 $\text{cmol}_c \text{ kg}^{-1}$ clay = dystrophic, 5-15 $\text{cmol}_c \text{ kg}^{-1}$ clay = mesotrophic, >15 $\text{cmol}_c \text{ kg}^{-1}$ clay = eutrophic)

The ECEC was determined as follows:

$$\begin{aligned} \text{ECEC} &= (Na^+ + K^+ + Ca^{2+} + Mg^{2+}) + Al^{3+} \\ &= \text{cmol}_c \text{ kg}^{-1} \text{ soil} \end{aligned}$$

The following equations were used to calculate the ESP % and EMP %:

$$\begin{aligned} \text{Exchangeable Na \%} &= (Na^+ (\text{cmol}_c \text{ kg}^{-1} \text{ soil}) \times 100) \div \text{ECEC} \\ \text{Exchangeable Mg \%} &= (Mg^{2+} (\text{cmol}_c \text{ kg}^{-1} \text{ soil}) \times 100) \div \text{ECEC} \end{aligned}$$

The following criteria was provided for identifying clay movement down in a soil profile:

- *For any part of A or E horizon having 15% or less clay, the B1 horizon must contain a minimum of 5% more clay than A or E horizon.*
- *When any part of A or E horizon has >15% clay, the ratio of clay percentage in the B1 horizon to that in the A or E horizon must be 1.3 or greater.*

When the above criteria was not met the soil profile was identified as being non-luvisol.

The estimated amount of haematite (Fe oxide) in each sample was calculated with the following equation:

$$\text{Redness Index (RI)} = \frac{a^* (a^{*2} + b^{*2})^{1/2} \times 10^{10}}{b^* \times L^{*6}}$$

CHAPTER 4

4. Soil colour relationships

4.1 Materials and methods

4.1.1 Data analysis and statistical methods

Soil colour was measured visually and spectrophotometrically as specified in Chapter 3. Correlation matrices were generated between the various colour components as well as between the selected chemical and physical soil properties in the Profile Database. A correlation matrix between spectroscopic Munsell colour measurements and soil pigmenting properties in the Profile Database were also generated using both Spearman's and Pearson's correlation coefficients. Spearman's correlation coefficients were used in the discussion to characterize the strength of the relationships. All analysis were performed with STATISTICA version 12.0.1133.6 (StatSoft, 2013).

Frequency plots (histograms) were constructed to illustrate colour notation matches and differences between the different colour measurement conditions (natural daylight, laboratory and spectrophotometer).

For data analysis and plotting purposes, Munsell hue was converted into a numerical value using a scale that increased from red (10R) to yellow (10YR). This was achieved by using the value preceding the letter abbreviation of each hue chart (Barron & Torrent, 1993). This means that for 10R, hue is 0, and for 10YR, hue is 10 (Munsell Color Company, 1980). Instances did occur where the Munsell hue 2.5Y had to be numerically modified to 12.5. The hue becomes progressively more yellow and less red as these numbers increase.

Detailed descriptions of each physical and chemical analysis performed on the soil properties in the Profile Database are outlined in Appendix 4. The process and reasoning for compiling the Land Type Survey is also found in Appendix 4.

The aim of this chapter is to quantitatively compare visual soil colour measurements (dry and moist state) made in natural daylight and laboratory conditions with measurements made with a spectrophotometer. The effectiveness of visual colour measurement guidelines as outlined by the Munsell colour system and FAO is also evaluated by comparing visual measurements made in the laboratory conditions and in natural daylight (measurements made in outdoor conditions). The relationship between spectroscopic colour measurements and %OC, CBD

Fe and soil texture will be investigated. Evaluation of the interrelationships between these soil chemical parameters will also be investigated.

4.2 Results and discussion

4.2.1 Relationship between visual and spectroscopic measured soil colours

In order to establish how each of the Munsell colour components (hue, value and chroma), measured visually under different conditions correlated to the spectroscopically measured colour components, a correlation matrix was constructed (Table 4.1). When classifying colour using Munsell colour chips, the individual colour increments of hue, value and chroma are very coarse. For example, only 4 hues were visually recorded for all soils analysed in this study. Therefore despite assigning/having numeric values for hue, value and chroma, these parameters represent a classification of the Munsell colour space and are actually discrete rather than continuous variables. Thus correlation values used in this study are actually calculated from discrete data. Using discrete data is not the most effective way of predicting linear relationships even if the data could have possibly been normally distributed (McKillup, 2005). Since the data used for creating the correlation matrixes were not normally distributed, Spearman's correlation coefficient allowed relationships to be created between the variables (colour components and soil properties) despite the relationships not being perfectly linear. This may have caused some relationships in this study to be stronger or weaker in comparison to Pearson's correlation values for the same set of relationships.

A complete correlation matrix for the relationship between all colour measurement conditions (visual and spectroscopic) and soil properties in the Profile Database are provided in Appendix 2, Table A2.5-A2.6. A complete correlation matrix for the relationship between all soil properties in the Profile Database is also provided in Appendix 2, Table A2.3-A2.4.

In Table 4.1 important relationships were observed between soil colour determined visually and spectroscopically. In terms of hue, dry spectroscopic measurements showed the strongest relationship with visual measurements made with viewing masks in natural sunlight conditions ($r = 0.78$). Dry spectroscopic value observations seems to have had the strongest correlation with value observations made with viewing masks in laboratory conditions ($r = 0.61$). This was also the case for chroma with chroma measured in the laboratory with viewing masks having the strongest relationship with the spectrophotometer chroma ($r = 0.77$). Post et. al. (1993) also conducted a similar experiment where visual colour estimations were compared to measurements made with a chromameter. They reported positive strong correlations, with r^2 values for hue, value and chroma being 0.96, 0.96 and 0.90, respectively.

Research done by Barrett (2002) on well-drained sandy soils also reported moderately strong correlations between spectrophotometer measurements and visual estimates made in the laboratory. The hue, value and chroma having an r value of 0.39, 0.84 and 0.87 respectively.

Visual laboratory and natural daylight (measurements made in outdoor conditions) colour measurements of dry soils made without viewing masks, both exhibited moderate to strong correlations with dry spectroscopic measurements. The dry visual laboratory measurements generally showed a stronger correlation with dry spectrophotometer measurements compared to natural daylight visual measurements.

Table 4.1: Relationship between visual colour measurement components and spectrophotometer colour measurement components in different conditions.

Colour Variable and Condition	Hue Dry Spectroscopic	Value Dry Spectroscopic	Chroma Dry Spectroscopic	Hue Moist Spectroscopic	Value Moist Spectroscopic	Chroma Moist Spectroscopic
Hue Lab** Dry	0.73			0.59		
Value Lab Dry		0.56			0.21*	
Chroma Lab Dry			0.71			0.62
Hue Daylight Dry	0.70			0.55		
Value Daylight Dry		0.45			0.28	
Chroma Daylight Dry			0.50			0.53
Hue Lab Dry (Masks)	0.63			0.65		
Value Lab Dry (Masks)		0.61			0.20*	
Chroma Lab Dry (Masks)			0.77			0.65
Hue Daylight Dry (Masks)	0.78			0.62		
Value Daylight Dry (Masks)		0.52			0.13*	
Chroma Daylight Dry (Masks)			0.67			0.59
Hue Lab Moist	0.70			0.60		
Value Lab Moist		0.46			0.21*	
Chroma Lab Moist			0.57			0.56
Hue Moist Daylight	0.67			0.55		
Value Moist Daylight		0.39			0.23*	
Chroma Moist Daylight			0.58			0.64

* Not significant at 0.01 level of probability

** Laboratory

In the moist state, spectroscopic measured hue and chroma measurements exhibited moderately strong correlations with both natural daylight and laboratory visual estimates. Moist spectroscopic hue observations having the strongest relationship with moist hue measurements made in laboratory conditions. In terms of chroma, moist spectroscopic measurements had the strongest correlation with moist natural daylight measurements ($r = 0.64$). Moist spectroscopic value measurements had very weak non-significant relationships with both natural daylight ($r = 0.23$) and laboratory ($r = 0.21$) measurements. A similar study based on the relationship between moist soil and chromameter colour measurements, have reported strong significant correlations between the colour components (Post et. al. 1993). The r^2 values for Munsell hue, value and chroma being 0.93, 0.92 and 0.89 respectively. A possible explanation for these stronger relationships could be the fact that visual measurements were made by ten different observers. Averaging the visual colour component measurements could have created stronger relationships with the chromameter measurements. Another explanation could be that less chromatic soil samples were used compared to this study, resulting in a narrower range of visual colour estimates.

The findings from this study suggested that visual laboratory colour measurements in both the dry and moist state had a stronger correlation with the spectrophotometer colour measurements when compared to visual natural daylight colour measurements. Generally all visual dry colour measurements have shown to have a stronger correlation to the spectroscopic colour measurements compared to moist visual colour measurements. The reason for this may be because the quantity of water added to each soil sample for the moist colour measurements were made subjectively, which could have resulted in the samples not being equally moist prior to its measurement. The use of viewing masks also showed to have a marginally stronger relationship with spectroscopic measured colour compared to visual measurements made without viewing masks.

Additional relationships between the different visual and spectroscopic colour components and conditions are displayed in Appendix 2 – Table A2.1 – A2.2. A Multi Factorial Analysis (MFA) was conducted, creating a correlation circle to visually illustrate the relationships between the different visual and spectrophotometer colour measurement conditions using Munsell hue, value and chroma (Appendix 2 – Figure A2.1).

4.2.2 The effect of using viewing masks in visual daylight and laboratory soil colour measurements.

The correlation matrix presented in Table 4.1 is useful for establishing the strength of the relationships between the various colour components, but it is not useful in determining how the various measurement techniques and conditions will affect the observed colour. This can be achieved by examining the differences between the individual colour components recorded for the same soils under different measuring conditions. Thus the difference between the colour components measured under different conditions was calculated for each soil (e.g. hue measured without masks – hue measured with masks). The residuals are graphically displayed in the form of histograms (Figure 4.1 - 4.4).

The residual difference between colour components measured visually in the laboratory and natural daylight, with and without the use of viewing masks are showed in Figure 4.1. The residuals for the colour component measured in daylight conditions with and without viewing masks are shown in Figure 4.1a. In the case of hue total agreement (i.e. residual = 0) between the two measuring techniques only occurred in 54% of the observations and for a large portion (36%) of the soils hues measured with the viewing masks tended to be more yellow. The use of viewing masks tended to increase the lightness (value) component of the soil showing a 33% occurrence of the -1 residual. Chroma measurements showed 50% total agreement, with the remaining residuals having a highly variable spread. According to Luo et. al. (2001), and as discussed in section 2.2.2, the large range of variability in chroma may be explained by the fact that humans have difficulty differentiating between colours having high chroma. These results suggest that when assigning individual colour components in natural daylight, the use of viewing masks do have an influence on the decision almost half of the time.

The residuals for the colour components measured with and without viewing masks in laboratory conditions are shown in Table 4.1b. There was a high level of total agreement (81%) for hue measurements. For value, 73% of the observations were in total agreement and chroma observations showed total agreement in 74% of the measurements, with the spread of the remaining residuals being highly variable. This suggests that using viewing masks in laboratory conditions will have less influence on colour designation than the use of viewing masks in natural daylight conditions. The reason for this is not clear, but may be due the fact that the lighting conditions in the laboratory are relatively constant. This ensures an environment where the effect of colour contrasts (e.g. light reflected from surrounding objects) can be controlled without the use of the viewing masks. In the field or in outdoor conditions, lighting cannot be controlled and the use of viewing masks ensures that the dimensions of the field of view are kept constant and the effect of colour contrasts are decreased (Atkinson &

Melville. 1985). Bhadra and Bhavanarayana (1996) and Erskine (2013) also made use of viewing masks in their studies for the exact reasons mentioned above. The occurrence of metamerism (Barron & Torrent, 1993), may also be a reason for the high level of agreement between the colour measurements made in laboratory conditions.

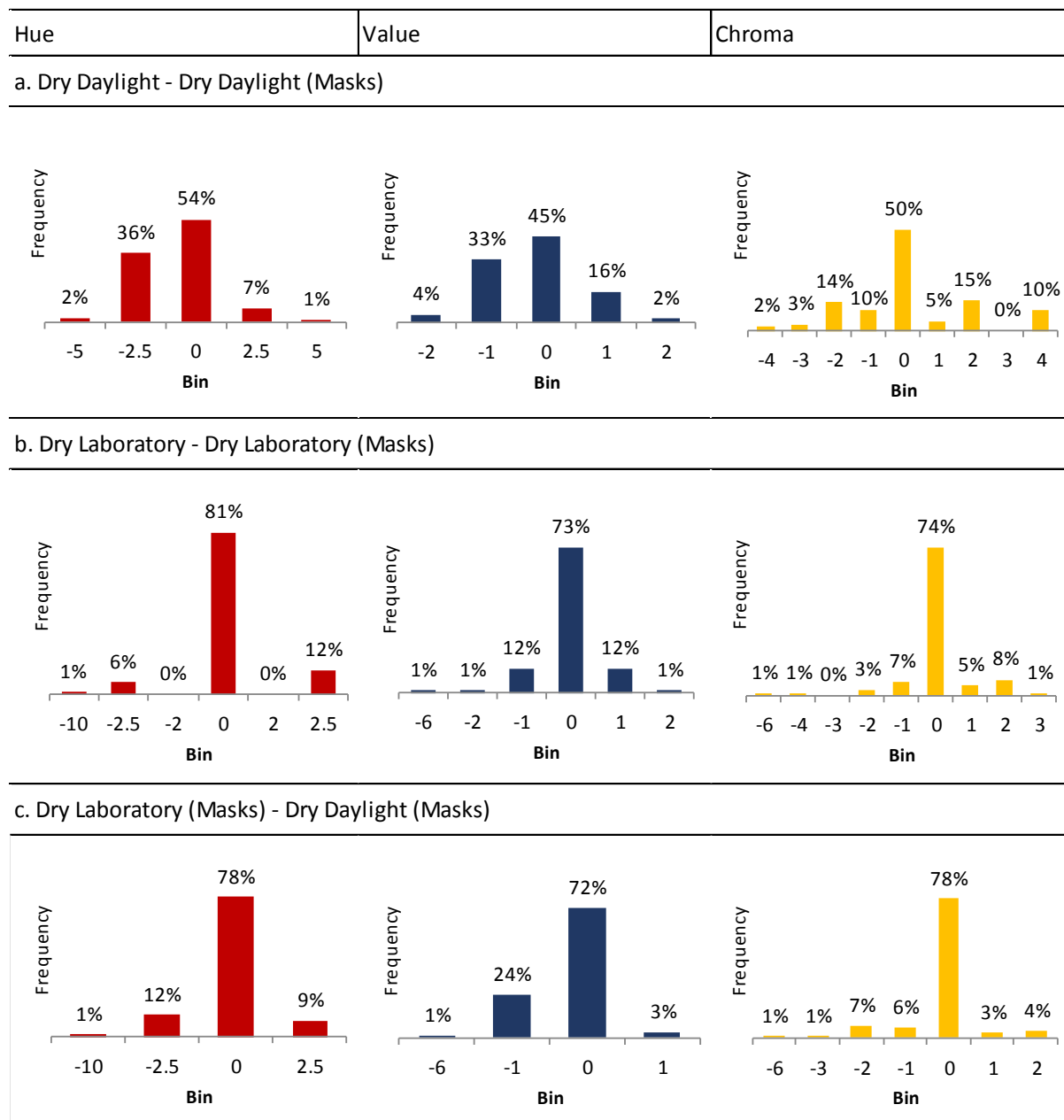


Figure 4.1: Histograms displaying the difference between visually measured dry colour components in different conditions. a) Visual daylight colour measurements made with and without viewing masks b) Visual laboratory colour measurements made with and without viewing masks c) Visual daylight and laboratory colour measurements made with viewing masks.

The residual differences between the colour components measured in natural daylight and laboratory conditions (with masks) are shown in Figure 4.1c. A similar pattern was observed for measurements without masks (data not shown). In general there was good agreement between colours measured in the laboratory and in natural daylight. In the case of hue and chroma, both components showed total agreement occurred in 78% of the observations. Value showed 72% total agreement between the observations, also showing 24% occurrence of the -1 residual. This implies that the soil values measured in the laboratory with the viewing masks occasionally tended to increase the lightness component of the soil. Reasons for not achieving 100% agreement between these measurements may be due to variable lighting intensities experienced when natural daylight measurements were made, that would have influenced the amount and intensity of light or radiation energy being reflected from the soil sample surface and Munsell colour charts (Barrett, 2002). These variable conditions could have influenced the observer to perceive the colour components of each soil differently due to the different daylight conditions.

4.2.3 Comparison between visual and spectroscopic soil colour measurements

Masks general facilitate colour assignments (Munsell Color Company, 1994), thus only colours measured using masks will be presented here. The comparison of colour components measured in the laboratory and natural daylight conditions with that of the spectroscopic measurements is given in Figure 4.2.

Visual dry hue measurements made in natural daylight conditions have shown to have the highest level of total agreement (60%) with the dry spectroscopic measurements. Only 51% of hue observations made in the laboratory agreed with spectroscopic measurements.

In both visual laboratory and natural daylight observations, the spectrophotometer tended to make soil hues redder in 32% of the observations. In terms of value, the spectrophotometer tended to make soils one value unit lighter (59%) compared to laboratory measurements (Figure 4.2a) and showed equal proportions (47%) of the 0 and -1 residual when compared to natural daylight measurements (Figure 4.2b). Spectroscopic chroma observations had 0% total agreement with both visual laboratory and natural daylight observations. When compared, the spectrophotometer tends to designate lower chroma values to soils than both visual laboratory and natural daylight colour measurements would. This means the eye tends to make colour more intense or colourful than the spectrophotometer.

Much of the divergence between visual and spectroscopic determinations as seen in Figure 4.2 can be attributed to methodological differences in precision level. Visual estimates of

Munsell chroma are more prone to be overestimated when compared to the corresponding spectrophotometer measurements. Causes for this phenomenon may include: i.) a preference on the part of the human observer for the higher chroma values, perhaps to better differentiate among similar colours as they progressively become darker (Luo et. al., 2001) and ii.) the ability of the human observer to match colours to small soil features, whereas the spectrophotometer only “sees” an average colour in an 8-mm circle. Features smaller than 8 mm with higher chroma are thus averaged with the surrounding soil colour.

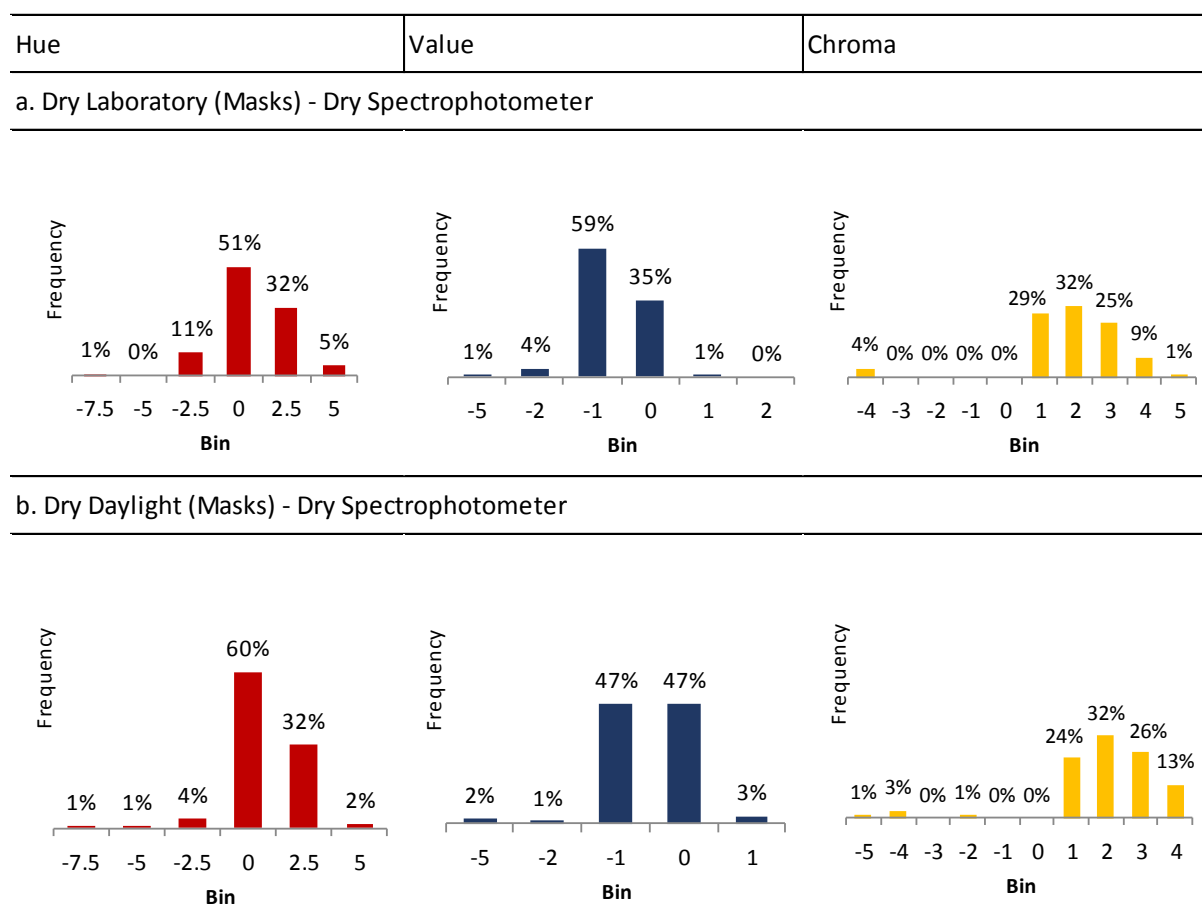


Figure 4.2: Histograms displaying the difference between dry visual and spectroscopic measured colour components in different conditions. a) Visual natural daylight measurements made with viewing masks and spectrophotometer colour measurements b) Visual laboratory measurements made with viewing masks and spectrophotometer colour measurements

4.2.4 Effect of moisture on soil colour

The residual differences between dry and moist visual and spectrophotometer observations are shown in Figure 4.3 In natural daylight conditions (Figure 4.3a) hue showed total agreement in 86% of the observations made visually in the moist and dry state. In terms of

chroma, 55% total agreement occurred between the moist and dry observations, and a 27% occurrence of the -2 residual. This means the human eye will tend to make soils more colourful in their moist state than in their dry state. For value measurements made in the dry state tended to make soil one value unit lighter (57 %) when compared to measurements made in the moist state.

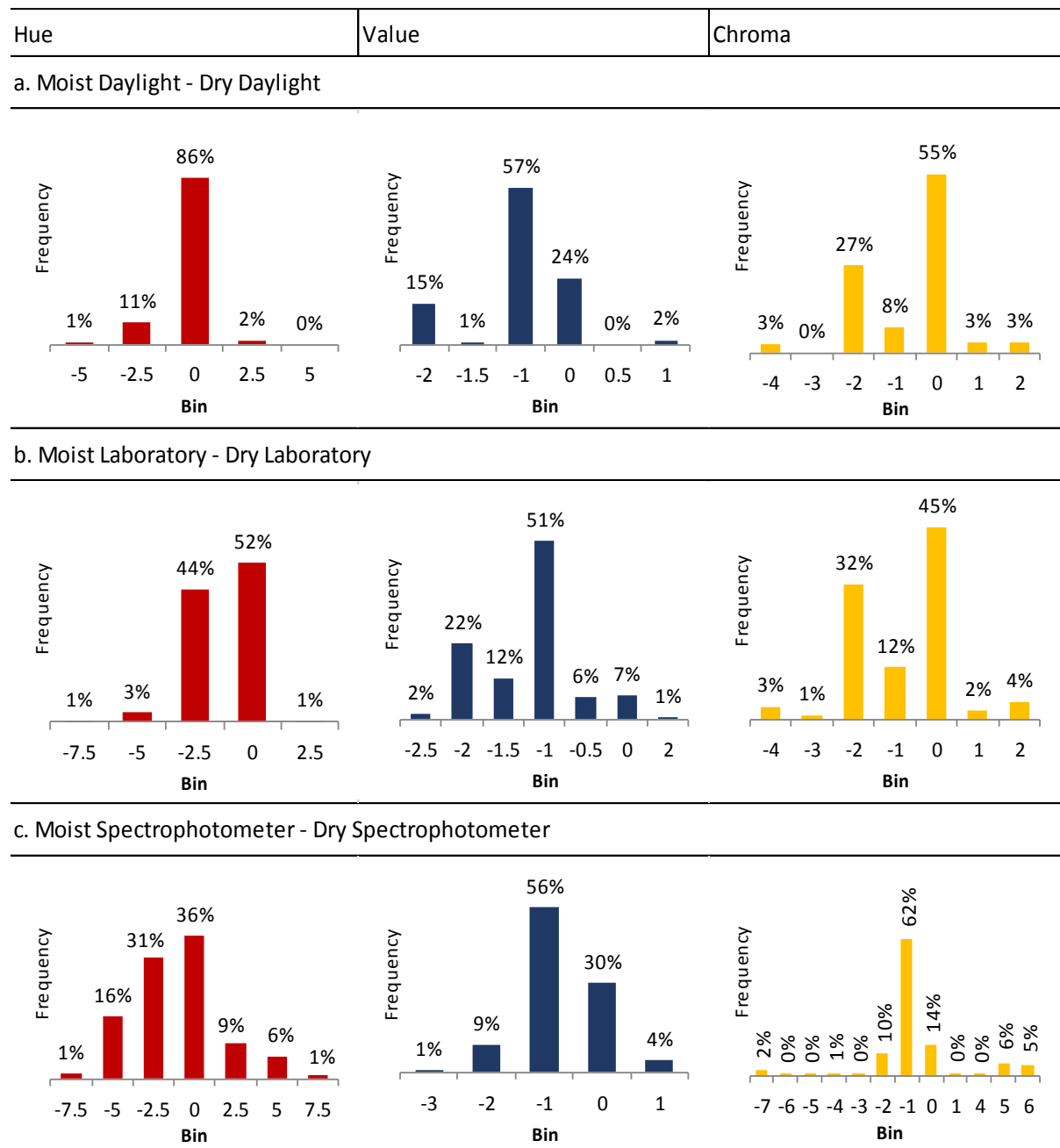


Figure 4.3: Histograms displaying the difference between dry and moist visual and spectroscopic measured colour components in different conditions. a) Moist and dry visual natural daylight colour measurements b) Moist and dry visual laboratory colour measurements c) Moist and dry spectroscopic colour measurements

Residuals of the measurements made visually in the laboratory (Figure 4.3b) showed similar trends to that of the visual natural daylight measurements, except for hue where similar proportions of the zero (52%) and -2.5 (44%) residuals occurred. Which means in laboratory conditions, moist soils will tend to have a redder appearance in 44% of the observations, when compared to its dry colour.

A strong trend existed for dry spectroscopic measured soils to be yellower when compared to their moist counterpart (Figure 4.3c). Spectroscopic value observations showed a similar trend to that of visual natural daylight and laboratory value measurements, having a high proportion (56%) of the -1 residual. In terms of chroma, dry spectroscopic measurements tended to make soils one chroma value more colourful when compared to their moist observations. A very low (14%) level of total agreement was also achieved for spectroscopic chroma measurements. The spectroscopic value and chroma results shown in Figure 4.3c is in agreement with the findings of Bhadra and Bhavanarayana (1997), who also reported that increasing soil moisture will negatively affect the lightness (value) and saturation (chroma) component of a soil measured with an instrument. This may be explained due to the fact that with soil moisture increase the spectral reflectance properties of the soil will decrease (Barrett, 2002). Shields et. al. (1966) on the other hand have suggested that there is no significant effect of soil moisture on spectrometric measured hue and chroma, but value was reduced by 1 and 2 units.

From the results in Figure 4.3, it is clear that when a soils moisture content changes from dry to moist, the human eye will tend to make the greatest colour designating changes in terms of value and chroma. Colour measurements made under natural daylight conditions accommodated colour changes due to moisture, mainly in the value and chroma components, while colour measured in the laboratory accommodated colour change in all three colour components. A possible explanation for this could be the different lighting conditions in visual natural daylight and laboratory colour measurements and also the method used to add moisture to each soil sample. These results for natural daylight and laboratory visual measurements can be confirmed by Post et. al. (1993) who also reported constant hue and variable value measurements for soils measured in dry and moist state. Interestingly the spectrophotometer made the greatest colour designation changes between dry and moist measurements in terms of hue and value. Meaning moist soils tend to be redder and darker, and not necessarily more colourful in terms of chroma. These spectroscopic results can also be supported by Post et. al. (1993). The reason for the observer and the spectrophotometer to make colour designation changes to different colour components is not clear. One possibility could be as a result of the 'book effect' whereby an observer tends to match the colour of the moist sample on the same hue page as the dry sample, rather than turning to another page.

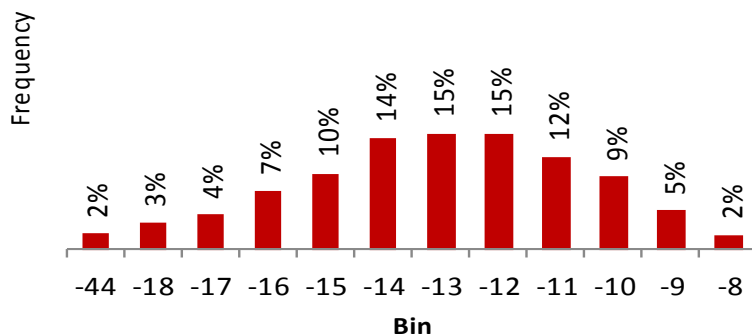
It is also instructive to assess wetting-induced colour changes to a soil sample in the $L^*a^*b^*$ colour space. The residual differences between dry and moist L^* , a^* and b^* observations made with a spectrophotometer. From the results in Figure 4.4, the overall lightness (L^*) of the soil decreased with an increase with the addition of soil moisture. From dry to moist state, the L^* value for majority of the soils decreased between 11 to 14 units. The a^* component of the spectroscopic measured soils mainly decreased 6 or 7 units from dry to moist state, and the b^* component decreased largely 9 or 10 units.

In terms of the $L^*a^*b^*$ colour space, the above results implies that dry soils will be lighter (higher L^* value) in colour, and will be located more on the red (a^*) and yellow (b^*) side of the $L^*a^*b^*$ colour space spectrum than moist soils (Figure 4.4). The lightness results agrees with the findings of other studies (e.g., Bedidi et. al., 1992; Bowers and Hanks, 1965). Bowers and Hanks (1965) investigated the effect of moisture content on spectroscopically measured soil colour lightness. They reported that increasing the soil moisture content will decrease soil lightness. Bedidi et. al. (1992) also found ferralitic soils to decrease in soil lightness with an increase in soil moisture, and also to have lower a^* and b^* values.

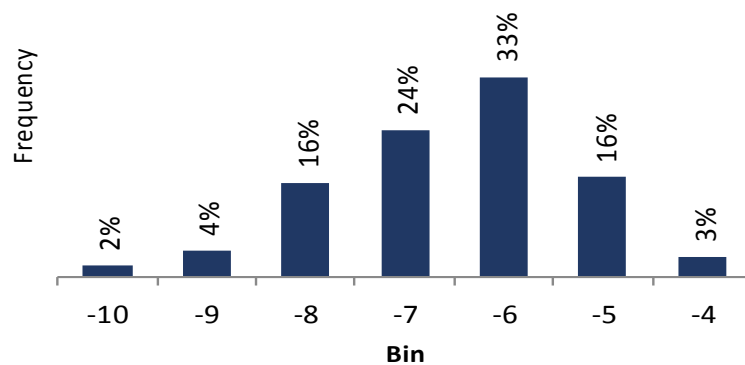
Since colour is one of the most useful features to characterize and differentiate between soils, accurate, precise, consistent and objective colour measurements is important. Thus to obtain this superior quality of colour measurements, visual measurements should be avoided. This is because, as seen from the results in this section, visually measured soil colour (laboratory and natural daylight) were not in total agreement with spectroscopically measured soil colour. This was ascribed to methodological differences in precision level. Visual soil colour measurements can thus become rather subjective when influenced by psychophysical (human perception) and physical factors (lighting conditions), which is not the case for spectroscopic colour measurements. For this reason, to ensure that the results in the next section, and for the rest of the study is relatively accurate, precise and consistent, only the spectroscopically measured colour data will be used.

Spectrophotometer (Moist) - Spectrophotometer (Dry)

*L



*a



*b

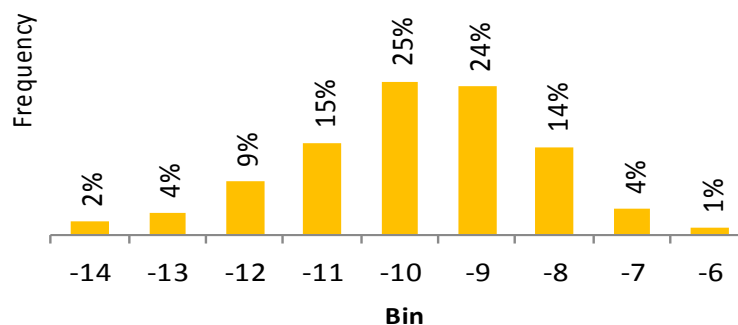


Figure 4.4: Histograms showing difference between L*, a* and b* values for moist and dry spectrophotometer measurements

4.2.5 Relationship between soil pigmenting properties and spectroscopic measured Munsell colour

Soil colour is commonly associated with three components, namely: SOM, Fe oxides and soil texture (Sánchez-Marañón et. al., 2004). In literature many studies have been published on the individual influence of SOM, Fe oxides and soil texture on soil colour. From these studies researchers would frequently report the influence other pigmenting properties had on their results (Galvao & Vitorello, 1998). According to Ibáñez-Asensio et. al. (2013) the influence of one pigmenting agent is not independent of the other pigmenting agents. Thus in order to establish the relationship between %OC, percentage CBD Fe and soil texture, a correlation matrix was constructed (Table 4.2).

Table 4.2: Relationship between percentage organic carbon, percentage CBD iron and soil texture.

Soil property	% Organic Carbon	% CBD Fe	Total Sand %	Total Silt %	Clay %
% Organic Carbon	1.00	0.59	-0.72	0.62	0.65
% CBD Fe		1.00	-0.80	0.54	0.85

* Not significant at 0.05 level of probability

From Table 4.2 %OC content showed moderately strong relationships with sand, silt and clay fractions. Sand being negatively correlated to %OC ($r = -0.72$) where silt and clay is positively correlated ($r = 0.62$ and $r = 0.65$, respectively). Similarly Ibáñez-Asensio et. al. (2013) who studied the relationship between the colour of 110 topsoils and various soil attributes from the south of Spain, also reported the clay fraction in soils to increase as the %OC content increased. This is because clay particles have larger surface areas than silt or sand particles, causing them to have a higher adsorption affinity for organic molecules. Konen et. al. (2003) also reported a strong positive relationship between %OC and clay content ($r^2 = 0.71$) in the hillslope soils of Iowa. The positive correlation between clay and SOM also exist because clay particles in association with SOM cements soil particles to ultimately form aggregates. This association also causes SOM to be insoluble in water allowing minimal losses of SOM due to leaching (Zech et. al., 1997). In low landscape positions moist and poorly drained soils are usually high in SOM since OM degradation is lessened due to the anaerobic conditions of wet soils. In these low positions clay accumulation would also be expected due to leaching of clay particles from higher landscape positions. Both Konen et. al. (2003) and Ibáñez-Asensio et. al. (2013) also reported strong correlations between %OC content and sand content.

Spielvogel et. al. (2004) suggested that relationships between lightness and SOM depend to a large extent on soil texture and its homogeneity. Even though soil texture might play a role in determining the SOM content of soils, climate is still considered the dominant factor determining SOM content in soils (Kirschbaum, 1995). Which could also explain the low OC content of the soils used in this study.

A correlation matrix was also constructed to determine the relationship of these pigmenting properties with various spectroscopic measured colour components (Table 4.3). The colour index, Redness Index (RI) was also included in Table 4.3. This index combines the three CIE L*, a* and b* values into an equation that estimates the hematite content of soils (Torrent et. al., 1983). To effectively predict the linear relationships between soil pigmenting properties and spectroscopic measured Munsell colour components it was necessary to use spectroscopically determined hue, value and chroma (HVC) data (continuous) rather than visually determined HVC data (discrete).

Table 4.3: Relationship between spectroscopically determined colour components and soil pigmenting properties.

Soil property and Colour component	% Organic Carbon	% CBD Fe	Total Sand %	Total Silt %	Clay %
Redness Index (L*a*b* Dry)	0.19	0.38	-0.15	0.03*	0.22
L* Dry	-0.25	-0.39	0.18	-0.06	-0.23
a* Dry	-0.45	0.09	0.08	-0.16	-0.01*
b* Dry	-0.38	-0.14	0.09	-0.10	-0.07
Dry Spec. Cont. Hue	0.22	-0.20	0.00	0.07	-0.05
Dry Spec. Cont. Value	-0.25	-0.39	0.18	-0.06	-0.23
Dry Spec. Cont. Chroma	-0.47	-0.05	0.11	-0.15	-0.06

* Not significant at 0.05 level of probability

** Spectroscopic Continuous

From Table 4.3 the RI showed the strongest correlations with Fe ($r = 0.38$). This was expected since the index is used to estimate the hematite content of soils. The positive relationship between RI and clay content ($r = 0.22$) may be due to the strong relationship seen between Fe and clay content in Table 4.2.

Organic carbon content in the soils showed weak relationships with all colour measurements components (Table 4.3). Weak negative correlations were observed between %OC and Munsell chroma ($r = -0.47$) and %OC and Munsell value ($r = -0.25$). Similarly, Ibáñez-Asensio et. al. (2013) who studied the relationship between the colour of 110 topsoils and various soil attributes from the south of Spain, observed weak negative relations between %OC and Munsell hue ($r^2 = -0.28$) and %OC and lightness (L^*) ($r^2 = -0.38$). Konen et. al. (2003) who studied the correlation between %OC and dry cultivated topsoil colour on hillslopes in Iowa, USA, also reported negative correlations between %OC content and Munsell chroma ($r^2 = -0.77$) and %OC content and Munsell value ($r^2 = -0.23$). This is in contrast to the findings of Yang et. al. (2001), who studied the effects of climate on different soils from China, and reported that %OC have a strong negative correlation ($r^2 = -0.88$) with soil lightness (L^*). Gunal et. al. (2008) also reported a strong relationship ($r = -0.72$) between SOM and soil lightness (L^*) from their study on the relationship between L^* , a^* and b^* and colour related soil variables on calcareous colluviums in northern Turkey. Although no correlation value was reported, Shields et. al. (1968) stated that from their study on the relationship between SOM and the colour of calcic and podzolic soils in Canada, that with an increase in SOM, Munsell value decreased.

From Table 4.3, Munsell hue showed very weak positive correlations to %OC content ($r = 0.22$) which is in agreement with the findings of Ibáñez-Asensio et. al. (2013) who also reported a weak relationship between SOM and hue ($r^2 = 0.36$). Table 4.3 also showed that with an increase in %OC the a^* and b^* components were negatively affected since the soils tended to become darker (more green and blue colours) as the %OC increased. Gunal et. al. (2008) also reported very weak relationships between SOM and colour components a^* and b^* ($r = -0.20$ and $r = -0.23$, respectively). Interestingly, Konen et. al. (2003) observed stronger relationships between Munsell value and SOM content when the data of the hillslopes were analysed together. Where Fernandez et. al. (1988) reported stronger colour-organic matter relationships between soils of different hillslopes in Indiana, USA. Ibáñez-Asensio et. al. (2013) and Schulze et. al. (1993) also speculated that the large extent and heterogeneity of the study areas could have caused weak correlations. The %OC correlations with colour variables in Table 4.3 may also improve if the data set used for this study are divided into smaller, similar geographical areas.

The results in Table 4.3 show that the % CBD Fe in soils have weak relationships with all the soil colour components. The colour components a^* and Munsell hue showed correlation values of 0.09 and -0.20, respectively. One would have thought that these two components would show stronger correlations with Fe since they directly reflect the redness (hematite content) of soils (Schwertmann, 1993). Surprisingly the colour component b^* is also very

poorly correlated with Fe content ($r = -0.14$). Gunal et. al. (2008) also reported a weak relationship between Fe content and a^* ($r = 0.09$) but a very strong relationship between Fe content and b^* ($r = 0.74$). The strong relationship with b^* was suggested to be due to the high goethite content (yellow colour) in the soils overshadowing the red pigmentation effect of the low hematite content in the soils. From Table 4.3 the lightness components of the soil, L^* and Munsell value both showed a correlation of -0.39 with Fe content. Where Gunal et. al. (2008) reported a weaker correlation value of -0.04 between L^* and Fe content. They suggested that the weak correlations may be due to the underlying interactions between the various pigmentation properties affecting the individual relationships with colour components.

Iron content and %OC content show a moderately strong positive correlation ($r = 0.59$). It is widely believed that the positive relationship between Fe and %OC content may be due to the stabilizing effect of Fe on SOM in soils (Wagai & Mayer, 2006). The positive correlation agrees with the results of other studies where the influence of Fe oxides on SOM stabilization were investigated (Huges, 1982; Evans & Wilson, 1985; Adams & Kassim, 1984; Kaiser & Guggenberger, 2000). The extensive and reactive surfaces of Fe oxides are often presumed to account for sorption and stabilization of SOM (Kaiser & Guggenberger, 2000). Wagai and Mayer (2007) conducted a study on the sorptive stabilization of SOM in surface mineral horizons and organic carbon (OC) - enriched, acid-leached subsurface horizons from a range of soil types and geographical areas, by hydrous Fe oxides. From their study they reported that the SOM fraction in the soils were many times greater than that of Fe oxides. They concluded that other mechanisms besides sorption to be responsible for OC storage in these soils. This is because Fe oxides are only able to sorb up to approximately their own volume in OM (Wagai & Mayer, 2007). Other possible stabilizing mechanisms suggested by Wagai and Mayer (2007) was that adsorbed OM could possibly have undergone humification reactions after sorption by Fe oxides that renders it insoluble, allowing significant volumes of SOM to accumulate in these soils. Possibly also the formation of metal-organic complexes in low-pH and high-OM soils or the formation of ternary OM-Fe oxide-clay associations. Extractable Fe oxides in soils are often found in association with phyllosilicate clays, helping to “glue” these clays together (Wiseman & Püttmann, 2006). Despite the significantly lower sorptive capacity of these low activity clays compared to Fe oxides, they have high surface-to-volume ratios, allowing to physically reduce enzyme and oxygen accessibility to OM (Wagai & Mayer, 2007). This means with highly reactive Fe oxides with less sorptive but more abundant clays may physically protect larger volumes of insoluble OM.

Galvao and Vitorello, (1998) studied the influence of SOM on the spectral properties of Fe when determining the colour of Brazilian tropical soils. From their study they reported that when SOM content in these tropical soils exceeded 1.7%, it reduced the relationship between

Fe content and soil reflectance by more than 40%. Similarly, Baumgardner et. al. (1969) also reported from their research in Tippecanoe County, Indiana, on the effects of OM on the multispectral properties of grey-brown podzolic soils, that organic matter seems to play a dominant role in imparting spectral properties upon soils when the OM content exceeds 2%. As OM content decrease below 2% it becomes less effective in concealing the spectral response effects of other soil constituents such as Fe. The greater the amount of OM, the stronger is its effect in reducing the colour features of Fe that can also effect the correlations between Fe and colour attributes (hue, value and chroma).

Another reason for the correlation between %OC and Fe content in the current data set may be the result of the geographic location of doleritic soils in SA. There is a high density of dolerite outcrops in the eastern side of the country (Decker et. al., 2011). The eastern side of the country also experiences higher rainfall and thus soils from this region may have a higher proportion of OC than soils from the drier regions.

The discussion above on the relationship between Fe, SOM / %OC and texture (clay) might explain the weak relationship of Fe with all the colour components in Table 4.3. The possibility exist for %OC in soils to be masking the colour of Fe, lowering the correlation values with all the colour components. Although all relationships were weak, %OC showed stronger correlations with hue, chroma, a^* and b^* than Fe suggesting that OC has a larger impact on these colour variables than Fe.

Texture could also have played a role in creating the weak correlations found between Fe and the colour components. Table 4.2 shows that Fe has a strong negative relationship with the sand ($r = - 0.80$) and a very strong positive relationship with the clay content ($r = 0.85$). Although similar relationships were observed for %OC and texture, Fe showed slightly stronger relationships with soil texture. Van Huyssteen and Ellis (1997) who studied the relationship between subsoil colour and degree of wetness on a selected site in the Grabouw district, Western Cape, also reported a very strong relationship ($r = 0.88$) between Fe and clay content in the colour-defined diagnostic subsoils that have been studied.

In terms of texture, sand, silt and clay contents showed very weak relationships with the colour components. According to Spielvogel et. al. (2004) soil lightness is effected by texture because silt and clay particles reflect more visible light than sand particles, resulting in lighter soil. The strongest correlations between the textures in Table 4.3 were for sand and soil lightness components (Munsell value and L^*) and clay and soil lightness components. Generally the lightness tended to increase with an increase in sand content. This makes sense since the total sand % showed a strong negative relationship with %OC where clay content showed a moderately strong correlation with %OC (Table 4.2). This agrees with the results of Konen et.

al. (2003) who also reported an increase in lightness with an increase in sand content and decrease in lightness with increased clay content. This is in contrast with the results of Ibáñez-Asensio et. al. (2013) who reported a negative relationship between Munsell value and sand content and a positive relationship with clay content. The negative relationship with sand is suggested to be due to SOM being able to easily coat the low specific surface area of the sand grains compared to the clay particles. Similarly Sánchez-Marañón et. al. (2004) also reported a weaker relationship between sand content and lightness due to free Fe oxides covering the silicate mineral particles. The overall weak texture-lightness relationships in Table 4.3 may be due to studying the effect of texture on soil colour independently from the combined effects of Fe and OM on soil colour (Ibáñez-Asensio et. al., 2013).

The results presented in this study as well as reports from the literature makes it clear that relationships between soil colour and 'pigmenting' soil properties are weak. These weak correlations might be due to the result of combining soils from a wide geographical region into one data set. It is clear that soil colour expression represents a complex interaction between chemical and physical soil components. The wide variety of soils used in this study makes it difficult to establish clear controls on soil pigmenting agents in red, yellow and neocutanic profiles. Grouping soils into areas with similar characteristics might provide better relationships with the various colour components.

Although the relationship between the various colour components and soil properties were established in this section, the processes and factors involved in their distribution through the soil profile still needs to be explored. As was briefly mention in section 2.3 bleaching in soils will tend to occur when the various pigmenting agents are removed from the profile. The processes involved in bleaching could be the same processes responsible for the distribution of colour pigments in soils. Thus in order to establish the process(es) responsible for bleaching in this study the spatial distribution of the bleached topsoils need to be determined. The relationship between topsoil bleaching and various lithological factors will need to be determined as well as the influence of different landscape, chemical and physical properties on the formation of bleached soil horizons.

4.3 Conclusion

In this chapter insightful relationships were observed between the various soil colour measurement conditions and soil colour components. The relationship between soil pigmenting properties and Munsell colour components have also provided some interesting results.

- The use of viewing masks in visual colour designations showed stronger relationships with spectroscopic measured colour than when viewing masks were not used.
- The results suggests that there is no great difference between using viewing masks in the laboratory or natural daylight when measuring dry soil colours.
- The spectrophotometer seems to make soils redder than measurements made in natural daylight and laboratory (with viewing masks) conditions.
- In general, the visually measured soil colour tended to be more chromatic compared to spectroscopic measured colour.
- Organic carbon content appears to negatively affect iron content-colour component relationships and vice versa. The geographical spread of these properties might have caused the unpredicted relationship.
- Weak relationships may be due to large spatial spread of the soils and the fact that soil colour expression represents a complex interaction between chemical and physical soil components.

CHAPTER 5

5. Properties of apedal soils with bleached topsoils: clues for genetic pathways

5.1 Introduction

The genetic and morphological significance of soil colour has been widely recognised by soil scientists. Although soil colour is of no direct agricultural significance, several soil properties such as soil mineralogy (lithology) and degree of degradation have been found to be strongly related to soil colour (Sánchez-Marañón et. al., 1996). Soil colour can also be indicative of pedoclimatic factors and the state of pedogenic evolution in soils (Delgado et. al., 1994). The distribution of soil properties such as, SOM (black), Fe oxides (red to yellow) and silicate mineral composition and content (white to grey) in soil profiles is believed to be closely associated with the soils moisture regime (Ibáñez-Asensio et. al., 2013). These soil properties are also said to be responsible for the colour of most soils and their distribution in soils are mostly the result of soil forming processes such as eluviation, illuviation, leaching and reduction (Jennings et. al., 2008).

In this chapter the three mechanisms of bleaching will be discussed which includes Fe reduction, lessivage and podzolisation. Also discussed is the relationship between all lithological factors (lithological discontinuities, parent materials and duplex soils) and the occurrence of bleaching. The influence of different landscape properties on the formation of bleached soil horizons will also be discussed.

5.2 Mechanisms of bleaching

The South African Soil Classification System (Soil Classification Working Group, 1991) uses soil colour to define certain diagnostic horizons such as the red apedal B, yellow-brown apedal B and E horizons. Schwertmann and Carlson (1994) reported that hematite and goethite are the dominant Fe oxides responsible for the red and yellow colours of soil. Iron content is presumed not to be exclusively correlated with soil colour and that the concentration, particle size and crystal structure of the Fe oxides will also influence soil colour. Goethite not only forms from the selective loss of hematite but is can also develop due to an increase in Al-

substitution (Schwertmann & Carlson 1994), leading to a loss of Fe and an increase in the Al-content of resistant Fe minerals.

In the absence of free carbonates three processes are generally responsible for soils changing colour from red to yellow and ultimately to grey (bleached). These processes include Fe reduction, leaching and podzolisation.

5.2.1 Bleaching due to reduction

Reduction in soils is a process driven by microbial activity. In aerobic conditions microbes consume OM that serves as the dominant source of electrons in soils (Chen et. al., 2003). This leads to the decomposition of OM and the production of carbon dioxide (CO₂) in aerobic environments. When oxidised, the electrons released are used in reducing reactions. Reduction of oxygen (O₂) can also occur in saturated soils, but only if O₂ is still dissolved in the soil solution (van Ranst & de Coninck, 2002). According to Vepraskas and Faulkner (2001) several conditions must be met for reduction in soils to occur. The conditions include: i.) soils must be water saturated to the extent where free movement of air supplying the O₂ is stopped; ii.) with slow O₂ diffusion, anaerobic respiration occurs and soil microbes will utilize other electron acceptors. The theoretical order of electron acceptors reduced after O₂ is: NO³⁻, MnO₂, Fe₂O₃, SO₄²⁻, and CO₂ (Fiedler & Sommer, 2004); iii.) water movement through the soil profile should be stagnant or very slowly moving to prevent an influx of oxygenated water; iv.) OM must be present to fuel a respiring microbial population (Vepraskas & Faulkner, 2001).

In terms of Fe reduction, anaerobic microbes can oxidise OM as an electron acceptor. Electrons are then donated to Fe oxides from where Fe³⁺ is reduced to soluble Fe²⁺. Cycles of wetting and drying have a pronounced effect on soil colour (Jennings et. al., 2008). The respiration rate of an air-dry soil immediately after its re-wetting is relatively high. Repeated cycles of wetting and drying, as well as aerobic and anaerobic cycles, increase respiration which implies an increased rate of OM depletion compared to conditions with constant water contents (Jennings et. al., 2008). These varying cycles of aerobic and anaerobic conditions in soils lead to the removal of soluble Fe³⁺ giving the soil its bleached colour (Kostka et. al., 1999).

According to Sánchez-Marañón et. al. (2004) SOM and Fe oxides are considered to be the dominant pigmenting agents in soils. This means bleaching would probably be noticed first in low Fe containing profiles, even though both profiles (bleached and non-bleached) may have been subjected to similar environmental conditions. According to Schwertmann (1993) a general misconception is that the colour of a soil caused by Fe oxide is only because of its

quantity in the soil. This is not true since the type(s) of Fe oxides in the soil will also play a principle role. Goethite may form when soils containing hematite are exposed to cooler climates with increased water activity and SOM content. Since hematite is a stronger pigmenting agent than goethite, a hematite increase of only 1% can change a soils hue from 2.5Y to 5YR (Torrent et. al., 1983). Soils with a high hematite content will thus not show redox features as readily as a soils with lower hematite contents. In well-drained conditions, the dehydrated or more crystalline hematite is relatively stable due to the lower activity of Fe (Wheeler et. al., 1999). Once the hematite is exposed to alternating redox cycles, the Fe becomes unstable and reduction takes place, which might lead to bleaching.

5.2.2 Bleaching due to lessivage

Lessivage is the vertical or lateral transfer of clay particles from an eluviated soil horizon to another horizon, called the illuviated horizon (Quénard et. al., 2011). This process has been described as a major or secondary pedogenetic process for many soil types and under many climate conditions.

Lessivage in soils due to chemical and physico-chemical mechanisms gives rise to three processes namely, particle mobilisation, particle transport and particle deposition (Quénard et. al., 2011). The nature and interaction of clay particles are functions of both clay mobilisation and flocculation. The interactions will again depend on the nature of the exchangeable cations on their surfaces and the presence of cementing agents such as OM (Amezketta & Aragües, 1995). The mineral composition of clays will also effect its mobilisation (Gal et. al., 1984). This means that soils rich in smectitic clays will disperse better than those rich in kaolinitic clays, illite or quartz because the surface charge of smectitic clays are much higher. According to Gal et. al., (1984) polyvalent cations cause flocculation at pH's below 5 because of a high Al^{3+} concentration in the soil solution. Flocculation will also tend to occur at pH values higher than 6.5 when a high Ca^{2+} concentration is present in the soil solution (Gal et. al., 1984). Even though these soils might have a high pH, clay dispersion will still tend to occur when there is a strong dominance of monovalent cations, particularly Na^+ , on exchange sites (Soil Survey Staff, 1999). Organic matter, Fe, Mn, silica and Al-oxides reduce soil dispersibility by binding soil particles which improves soil stability and therefore decreasing mobilisation (Chenu et. al., 2000).

To increase clay mobility, Fe as stabilizing agent need to be removed from the profile. As explained above Fe can be removed from soils through reduction. As the Fe content in soils progressively decrease, Na^+ as dispersive agent may cause clays to become unstable that

can ultimately lead to clay dispersion (van Zijl et. al., 2014). When soils become saturated, dispersed clays are removed through eluviation ultimately leaving behind a bleached coarse textured soil matrix. Since lessivage causes textural contrasts in soils, reducing conditions for the removal of Fe is promoted, which in turn will again promote lessivage. In contrast to this belief of Fe being a stabilizing agent of clays in soils, Fanning and Fanning (1989) reported that it may be possible for free Fe oxide particles to move with dispersed clay particles through the soil profile. This is because Fe oxide particles are typically very fine and may attach to the silicate clay particles as it is being eluviated. They also stated that the ratio of free Fe oxides to clay often remains nearly constant with depth in lessivaged soils, thus implying the movement of Fe oxides with clays.

Not all textural contrasts in soils are due to lessivage (Chittleborough, 1992). In situ formation of clays is also possible and is a type of neoformation called argillation (Fanning and Reybold, 1968). Relative clay enrichment in the B horizon can also be caused by sand and silt destruction due to weathering in the A horizon. This is achieved by preferential erosion of finer materials from additions of coarser materials to the top horizon, reduction of silt and coarse clay particles to fine clay through crushing or grinding processes (comminution) in the B horizon (Oertel (1968); Smeck et. al., (1981)) and/or bioturbation which can move relatively coarser materials to the surface horizon (Nooren et. al., 1995).

5.2.3 Bleaching due to podzolisation

According to the South African Soil Classification System (Soil Classification Working Group, 1991) a podzol B horizon forms underneath an orthic A or E horizon on sandy parent materials under fynbos vegetation, and receives a winter or annual rainfall of more than 350 mm. This B horizon is characterized by an enrichment of OM and sesquioxides through illuviation. This horizon, however, does not show a marked increase in clay content since these soils has a low clay forming potential. The A horizons of hydromorphic podzol soils are usually very dark in colour due to the masking effect of residual humus, even though sesquioxides have been removed causing the sand-sized mineral grains to present a bleached appearance (Fey, 2010). When present, the E horizon has a bleached grey almost white colour (Mokma et. al., 2004). The bleached colour in this case is not the result of lessivage or reduction of Fe oxides (Fey, 2010). In non-hydromorphic podzol soils the E-B transition is wavy and in hydromorphic podzols it is smoother due to a fluctuating water table in high rainfall areas or its location in low lying terrains positions (Fey, 2010). The processes proposed to explain podzolization (Sauer et. al., 2007) includes: the formation of water-soluble complexes of organic acids with

Fe, Al and Si. Also the reduction of Fe by organic acids and migration in reduced metal-organic complexes and translocation of Al, Si and Fe as inorganic colloidal sols.

5.2.4 Bleaching as defined by the South African Soil Classification System

According to the South African Soil Classification System (1991), our current understanding of bleaching is based on the formation of a diagnostic E horizon. Soil profiles that contain low chroma or greyish colour patterns, such as diagnostic E horizons, are commonly used to predict where seasonal saturation occurs in soils (Daniels et. al., 1971). Diagnostic E horizons develop from a temporary build-up of water on a less permeable B horizon which results in anaerobic conditions (Soil Classification Working Group, 1991). As mentioned previously, in these anaerobic conditions micro-organisms reduce Fe^{3+} to Fe^{2+} in the absence of O_2 (van Tol et. al., 2013). In this soluble state Fe^{2+} can be leached predominantly in a lateral direction and to a lesser extent in a vertical direction. Vertical water movement depends on the clay content of the B horizon that will restrict water flow in a vertical direction. When sufficient leaching of Fe^{2+} has taken place, only the bare grey silicate minerals remain in the soil horizon (Jennings et. al., 2008). Soil organic matter responsible for the dark brown colour of soils are also broken down during the reduction process that further promotes the grey colour of this bleached horizon (van Tol et. al., 2013).

The process of ferrollysis is responsible for the breakdown of clays in the E horizon (le Roux et. al., 2005). In this process Fe^{2+} replaces the basic cations that occur on exchange sites of clays in O_2 poor conditions, which results in the leaching of these basic cations (van Ranst & de Coninck, 2002). In oxygenated conditions Fe^{2+} is again oxidised to Fe^{3+} that produces exchangeable H^+ . These exchangeable H^+ molecules attack clay mineral structures causing the release of silica and aluminium (van Ranst & de Coninck, 2002).

In cases where E horizons overly horizons considered to be non-restrictive to vertical water flow (yellow-brown apedal B and neocutanic B horizons), lateral flow would become limited. The general understanding is that when the transition from the A to the E horizon is distinct rather than gradual, lateral movement occurs predominantly in the E horizon (van Tol et. al., 2013). A gradual transition would then indicate vertical water movement. The same principle applies to the transition from the E to the B horizon. This will result in reduction and vertical eluviation of colloidal material. Ponding and formation of perched water tables may also develop on low permeable layers below the B horizon. During extreme events this water table might reach the A horizon,

It sometimes so happens that during heavy rainfall events so-called well-drained soils can become saturated to the soil surface. Here lateral water flow would occur due to the higher

presence of macropores in the A horizon as a result of more OM and microbial activity (Jennings et. al., 2008). Due to a generally higher SOM content in surface horizons, reduction of Fe through microbial activity will be accelerated in these surface positions compared to the subsoils. When these high rainfall events occur, more intermitted water flows in the topsoils can result in the development of bleached topsoils (Van der Waals, 2013). Bleached topsoils have the same colour criteria as diagnostic E horizons (Soil Classification Working Group, 1991). Bleached A horizons are only recognized on a family level for soil forms containing pedocutanic, lithocutanic and neocutanic subsoils. These soils are considered to be well-drained, but since the subsoil is identified by its cutanic nature it is suggested by Van der Waals (2013) that topsoil bleaching might be the result of clay illuviation.

5.3 Bleaching due to lithological differences in soils

It is a widely held view that a strong texture contrast between surface and subsurface soil horizons has a marked effect on soil hydrology and on conditions for plant growth (Chittleborough, 1992). These soils also called duplex soils (Northcote, 1979) have a strong developed B horizon with marked increase in clay compared to the weakly structured overlying horizon (Fey, 2010). The marked clay increase in the B horizon results in a strong blocky, prismatic or columnar structure with cutanic features, clearly indicating the illuviation of clays. The development of E horizons and in some cases bleached A horizons form part of the diagnostic criteria for duplex soil forms in the South African Soil Classification System (Soil Classification Working Group, 1991). Fey (2010) suggested that many duplex soils also owe their horizonation partially to a binary origin where a colluvial or aeolian layer has been deposited on soil materials which has developed in situ from weathering rock. In these situations where soils within the same profile are genetically unrelated it can be said that the soil contains a lithological discontinuity (LD). The presence of an E horizon in these soils is often associated with LD within the profile (Fey, 2010). According to Fey (2010) genetic parallels can also be drawn between bleached topsoils and E horizons. He describes bleached topsoils as being a weaker expression of an E horizon. Thus it would be important to establish if bleached topsoils that occur on weakly structured subsoils to also be related to LD.

In soil science a LD is when there is a significant change in the particle size distribution or mineralogy of a soil that presumably indicates changes in the lithology of soil parent material (Phillips & Lorz, 2008). It can be represented by a more or less horizontal boundary between two materials in a soil profile (Arnold, 1968). According to Phillips & Lorz (2008) LDs may include discontinuities in texture, structure, fabric, geochemistry and mineralogy that occurs due to landform processes of transformation and deposition. Depositions (additions) to a soil

profile can include loess, which is air transported (aeolian) silt, or differences in the sedimentation conditions of alluvial and colluvial materials (Ande & Senjobi, 2010). Other indicators of discontinuity in a soil profile include stone lines that are formed due to colluvial processes, and also mottled features or indurated zones between adjacent soil horizons (Ande & Senjobi, 2010). When analysing LD's the general aim is to identify soil layers that might explain the pedogenic processes that took place in the original layered parent materials. The most reliable way of recognizing LD's is the use of index parameters that is based on a strong macroscopic contrasts, such as the particle-size distribution of the whole non-clay fraction of soils (Lorz, 2008).

Two methods that can be used to identify LD's in a soil profile include the Uniformity Value (UV) of Cremeens and Mokma (1986) and the Comparative Particle Size Distribution (CPSD) Index of Langohr et. al. (1976). Both of these methods supplemented and built on the traditional field-identification of discontinuities by suggesting the possibility of other unseen discontinuities in the soil profile (Rindfleisch & Schaetzl, 2001). These two indices are not reliant on soil colour and soil structure, which make them easy to use, unlike other methods that can be more labour intensive, such as heavy metal separation (Asamoah & Protz, 1972) and elemental analysis (Marsan et. al., 1988). The two methods uses particle-size data independent of a clay fraction, which will exclude the effect of clay illuviation (Rindfleisch & Schaetzl, 2001).

5.4 Landscape properties and the occurrence of bleaching

Hillslope soils that are hydrologically linked are called catenas (Milne, 1935). The catenal concept has demonstrated its broad geographic applicability in the discipline of soil classification (Khomu et. al., 2011). Central to catena formation is the mobilization of solutes, colloids and particles in upslope positions and their redistribution and transfer in downslope positions ultimately leading to the differentiation in soils across hillslopes (Huggett, 1975). Different degrees of soil differentiation and soil properties along catenas is caused by differences in mobilization mechanisms, transport pathways of materials and total water fluctuations (Khomu et. al., 2011). According to Sommer and Schlichting (1997) catenas can be classified in theory based on their chemical and morphological heterogeneity between crest and valley bottom positions as they respond to soil forming factors such as rainfall, lithology and topography.

The influence that soil water content may have on soil morphology and therefore soil classification varies depending mainly on variations in the topography and the soil type (van

Huyssteen et. al., 2010). Geomorphological properties that may have an influence on the soil water content includes: terrain unit, slope shape, slope angle and terrain aspect. The influence of geomorphological properties on soil water content is often combined with other soil properties such as the presence or absence of an impeding layer (Lin et. al., 2006).

On the South African Highveld a sequence of soils also known as the “plinthic catena” is characterised by a grading of well-drained red soils in crest positions, well-drained yellow-brown soils in midslope positions and poorly drained bleached soils in footslope positions (Van der Waals, 2013). There is a general increase in wetness from crest to the footslope positions that also leads to the formation of different coloured Fe-minerals in these positions. As mentioned before, hematite represents red soils where goethite represents yellow soils (Schwertmann & Carlson, 1994). The Munsell hue ranges assigned to these red and yellow soils form the basis for distinguishing between the red apedal and yellow-brown apedal B horizons (Soil Classification Working Group, 1991). The bleached coloured soils in footslope positions is the result of increased soil wetness and leaching that causes the reductive removal of Fe. The plinthic subsoil horizons that occur beneath the red apedal, yellow-brown apedal, E and occasionally Orthic A horizons, is indicative of a fluctuating water table and more permanent water table at depth (Soil Classification Working Group, 1991).

According to Fey (2010), A horizons that form on plinthic soils are often bleached. The formation of bleached topsoils on red and yellow-brown apedal subsoils are currently not recognised in the South African Soil Classification System (South Classification Working Group, 1991). This may be due to outdated soil survey methodologies, where horizon sequences are always classified from the top down. The occurrence of bleached topsoils on well-drained subsoils contradicts our current understanding of bleaching, which is based on the formation of diagnostic E horizons (Soil Classification Working Group, 1991).

The objective of this chapter is to establish the occurrences of bleached profiles in relation to geomorphic attributes, lithology and chemical and physical properties. The occurrence of topsoil bleaching in relation to various subsoil types and soil forms will also be investigated.

5.5 Materials and methods

5.5.1 Data analysis and statistical methods

Dry soil colour was measured visually and spectrophotometrically as specified in Chapter 3. From the spectroscopic measured colours two profile groups were created based on the colour of each topsoil. Each A horizon was classified as bleached or non-bleached using the dry

colour criteria of a Diagnostic E horizon as specified by the Taxonomic system for South Africa (Soil Classification Working Group, 1991). The colour of the topsoil defined the grouping of the whole profile, thus B horizons having a bleached topsoil fell into the bleached profile category, although the B horizon itself was not bleached. All colour classifications were based on spectrophotometer colours.

Differences in properties of these two groups were determined statistically. Normality tests were conducted on soil parameters containing continuous data. To test the significance ($p < 0.05$) of bleaching in each of these parameters, a one-way analysis of variance (ANOVA) was performed and bar graphs were generated to illustrate the results.

For soil parameters consisting of discrete data, categorized histograms were constructed to illustrate the frequency of bleached and non-bleached profiles in the various groups. The significance between the different frequencies was evaluated at a 5% level using the Chi-Square (χ^2) test. Histograms were also generated for the occurrence of bleached topsoils on diagnostic apedal subsoil horizons and various soil forms. These analysis were performed with STATISTICA version 12.0.1133.6 (StatSoft, 2013).

5.6 Results and discussion

5.6.1 Bleached topsoils identified by three measurement conditions.

In this section the effect of different soil colour measurement conditions on bleached colour recognition was investigated. The frequencies of bleaching measured visually, in both natural daylight and in the laboratory, and spectroscopically are given in Figure 5.1. Measurements made with the spectrophotometer identified a higher frequency (47%) of bleached topsoils compared to the visual measurements (Figure 5.1). This was expected since the results presented in Figure 4.2 (section 4.2.3) have showed visual measurements when compared to spectroscopic measurements, showed no agreement in terms of chroma and only 47% agreement with value estimations. Spectroscopic chroma measurements tended to be lower, making the soil colour less intense. These trends correspond with the general recognition of bleached (E) horizons, that is soils with high value and low chroma.

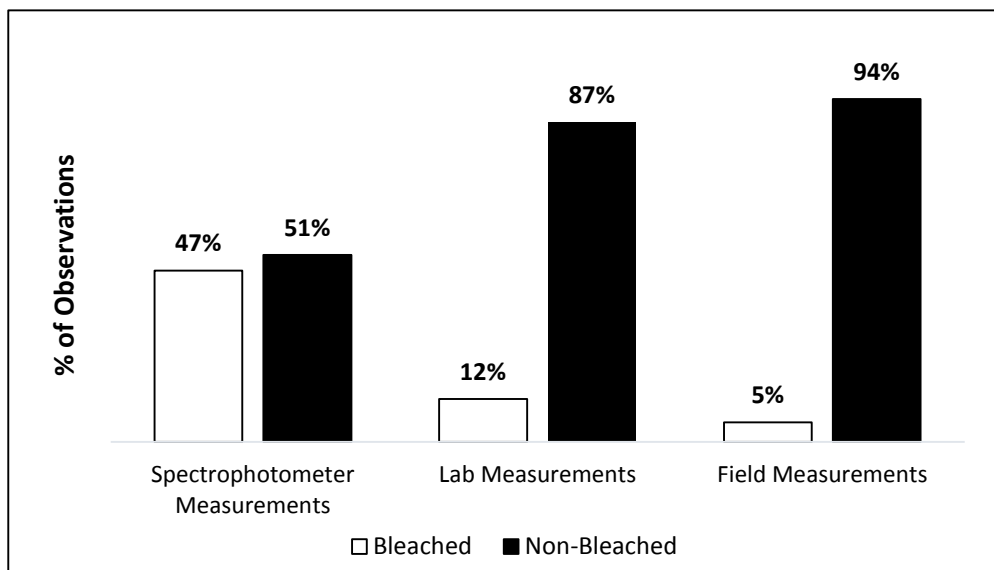


Figure 5.1: Classification of topsoils into bleached and non-bleached categories based on various measurements techniques and conditions.

As discussed in Section 4.2.3 much of the divergence between visual and spectroscopic determinations can be attributed to methodological differences in precision level. Observers tending to change colour in terms of chroma as they progressively become darker. The instrument also possess a higher sensitivity to the reflective properties of soils than the human eye, making soils appear lighter and less intense due to the increase of spectral reflectance from the soil surface. Another possible reason for this could be as a result of the 'book effect' whereby an observer does not have all the colour chips available in one view and thus the observer will compensate for changes in hue by assigning a higher chroma.

When visually measuring soil colour, the human eye seems more prone to classify a soil horizon as non-bleached (assigning higher chroma values). Visual colour estimates made in the laboratory showed a higher occurrence (12%) of bleached topsoils compared to natural daylight measurements (5%). Colour assigned under different lighting conditions is a large source of variation for visual soil measurements. Even slight changes in laboratory or natural daylight conditions could have influenced colour assignments, thus to remain objective it was decided to use colours measured spectroscopically in the comparison of the properties of bleached and non-bleached profiles.

5.6.2 Geographic location of bleached and non-bleached profiles

The map in Figure 5.2 illustrates the spatial distribution of bleached and non-bleached soil profiles across South Africa. Figure 5.3 illustrates the proportion of bleached and non-

bleached profiles in each province. The highest occurrences of topsoil bleaching were recorded in the Free State and Western Cape and the lowest in the Northern Cape and North West province. The spatial distribution of bleached profiles throughout South Africa, illustrates the wide range of conditions under which these soil will form. As such, the physical and chemical controls that result in topsoil bleaching are likely to be complex. The geomorphic, geological, chemical and physical properties are presented below in an effort to try confine the major controls on topsoil bleaching of apedal profiles.

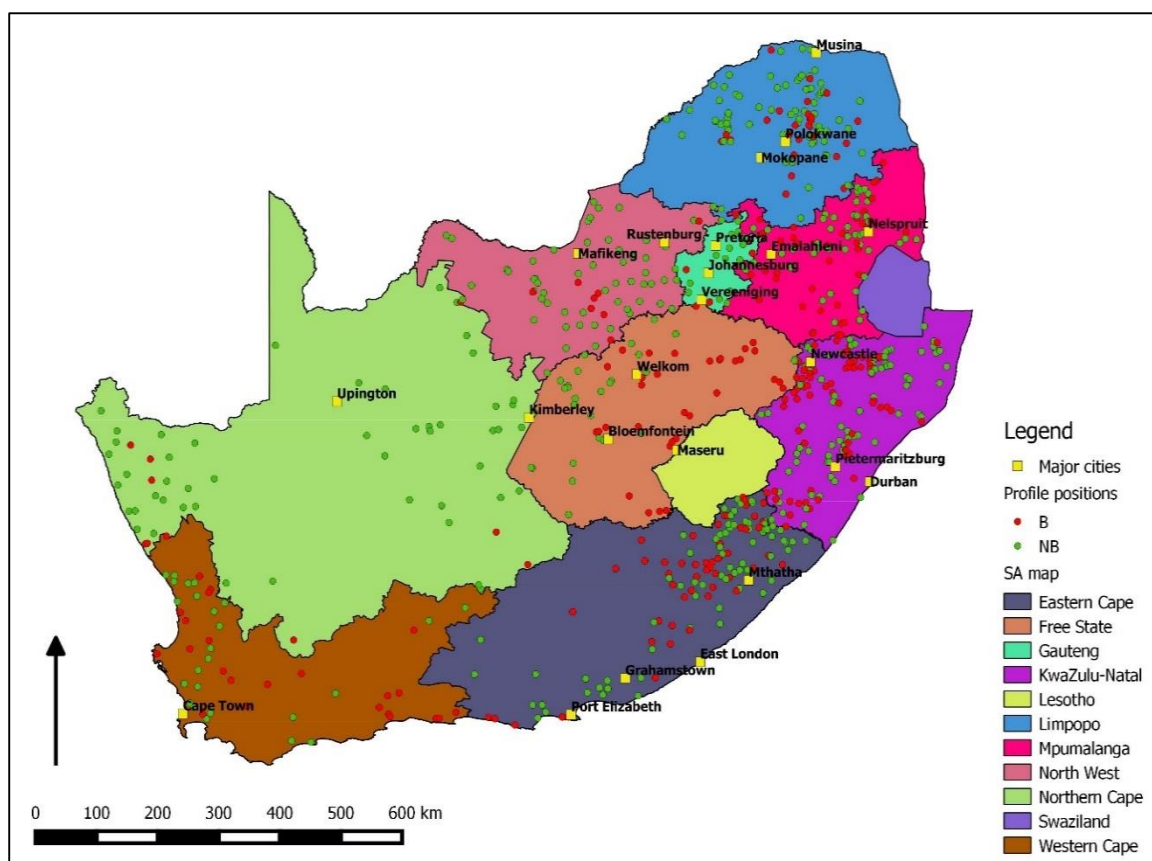


Figure 5.2: The spatial distribution of bleached and non-bleached soil profiles across South Africa as was identified with the spectrophotometer soil colour measurements.

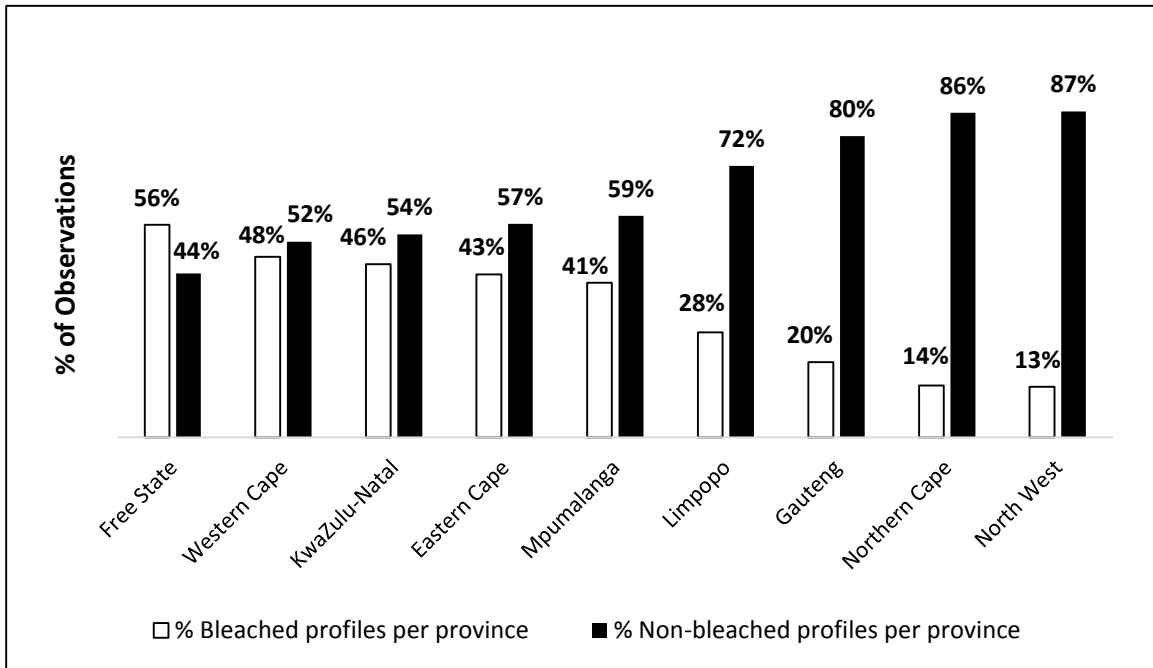


Figure 5.3: The proportion of bleached and non-bleached profiles occurring within each province of South Africa.

5.6.3 Geomorphologic relationships with topsoil bleaching

It has been proposed by van Huyssteen et. al. (2010) that bleaching or lightening of soil horizons is related to landscape properties. To determine the occurrence of topsoil bleaching on selected landscape properties, categorized histograms and bar graphs were constructed (Figure 5.4 – 5.9).

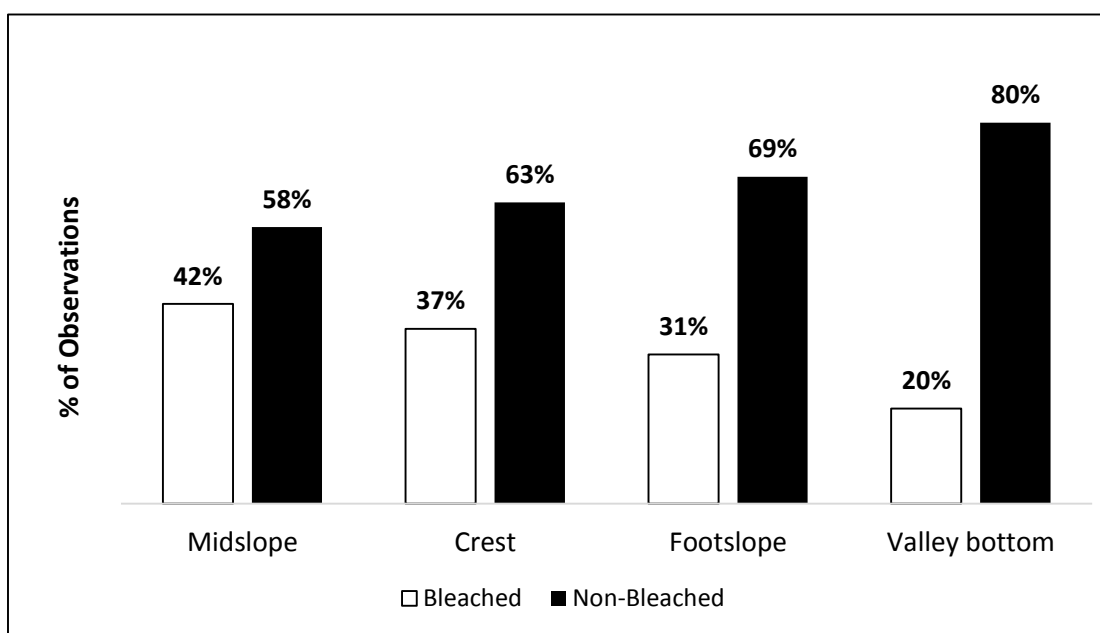


Figure 5.4: Frequency of topsoil bleaching on different terrain units (p-value = 0.03)

The results in Figure 5.4 show that the occurrence of bleaching was different ($p = 0.03$) on the various terrain units. The occurrence of topsoil bleaching in decreasing order is as follows: midslope > crest > footslope > valley bottom. This sequence is not consistent with a logical hillslope hydrology sequence. A study by Jennings et. al. (2008) on the redox conditions related to water flow in selected soils of the Weatherly catchment in the Eastern Cape, reported that the period of water saturation in soils is shorter on higher slope positions when compared to lower slope positions. From our current understanding of bleaching, soils need to be leached of Fe oxides and OM to expose bleached colours. Both of these pigmenting agents are effected by duration of water in the soil profile.

Fanning and Reybold (1968) identified bleached topsoils occurring in poorly drained soils but not very poorly drained soils. In the case of very poorly drained soils, OM build up was sufficient to prevent bleaching, while in the poorly drained soils the wetness was sufficient to result in Fe reduction but insufficient to result in OM accumulation. Thus bleached topsoils are likely to form in landscape positions that are prone to periodic rather than permanent saturation. On this basis one may expect footslope and valley bottom positions to show low incidences of bleaching. The occurrence of darker or non-bleached topsoils in lower landscape positions was also observed by Peterschmitt et. al. (1996), who reported yellow-brown and dark brown soils on footslope and valley bottom positions, respectively along a toposequence developed from weathered schists in Western Ghâts, India. However, it needs to be kept in mind that red or yellow-brown apedal soils should never be very poorly drained, so it is unlikely that saturated soil conditions can account for the low incidences of bleaching observed in footslope and valley bottom positions. In fact, lower members of the Highveld catena are usually characterised by bleached A and E horizons (Van der Waals, 2013).

Although no terrain positions were reported, Van der Waals (2013) conducted a study on the occurrence of topsoil bleaching on well-drained (red apedal and yellow-brown apedal B and E horizons) and poorly drained profiles (hard plinthic, soft plinthic and G horizons) in a plinthic catena on the Mpumalanga Highveld. He reported that A horizons overlying yellow-brown apedal B subsoils approached the same colour as A horizons overlying E horizons, suggesting these A horizons have similar water regimes. Van der Waals (2013) also reported that these bleached A horizons grade into wetter A horizons overlying E horizons further down slope. From these results he then proposed topsoil bleaching to develop in a similar way Jennings et. al. (2008) proposed E horizons to develop when subjected to lateral removal of colloidal materials. Which is that during periods of high and intense rainfall, restrictive layers (pedogenic or lithogenic induced), characteristic of a plinthic catena soils, underlying a well-drained profile may cause water to accumulate throughout the soil profile. The topsoil contains a higher OM content than the subsoil, accelerating bleaching processes (Fe oxide reduction) by respiring

microbial populations. This is not the case for the subsoil since it contains much lower levels of OM (Jennings et. al., 2008). When the topsoil becomes unsaturated, soluble Fe and dispersed clay are leached from the topsoil to the subsoils or laterally downslope. The lateral removal of Fe and colloidal material in the A horizon is then achieved with intermitted additions of water to the soil profile during rainfall events compared to the prolonged lateral water movement required to form an E horizon (Van der Waals, 2013).

Lateral movement of water through a landscape requires the development of hydraulic gradients. Research by van Tol et. al. (2013) on the development of E horizons from the Land Type Database has reported that in a given landscape, crest positions are normally associated with low gradients and the development of a hydraulic gradient would be low, whereas midslope positions have generally steeper slopes which would favour lateral water movement in the landscape, ultimately encouraging the formation of E horizons. If the bleached topsoils in this study formed in a similar manner one could then expect bleached topsoils to occur on terrain position where hydraulic gradients exist, such as the midslope. This may then explain the high incidences of bleaching on the midslopes. Although these mechanisms might give explanations to the occurrence of topsoil bleaching on well-drained subsoils and also possibly why they occur in midslope positions, the high occurrence of bleaching on well-drained crest positions is not easy to explain.

Figure 5.5 shows the occurrence of topsoil bleaching in relation to slope shape. The occurrence of bleaching on the three dominant slope shapes is significantly different ($p < 0.01$). The occurrence of topsoil bleaching decreased in the following order convex > conclave > straight slopes. These results are not expected and difficult to interpret especially in the light of the terrain unit results in Figure 5.4. Although not always the case, crest positions are usually associated with convex slopes, midslopes with straight slopes and footslope positions with concave slopes (Conacher and Dalrymple, 1977). Thus it is difficult to relate the two sets of data together. One possible reason for this is the subjective nature and inconsistencies between surveyors in the assignment of both slope shape and terrain unit. A more objective approach using digital elevation models (DEM's) to assign terrain unit and slope shape may provide more accurate data for analysing bleaching occurrences on the various morphological terrain units (van Tol, et. al. (2013); Lambrechts & MacVicar (2013)).

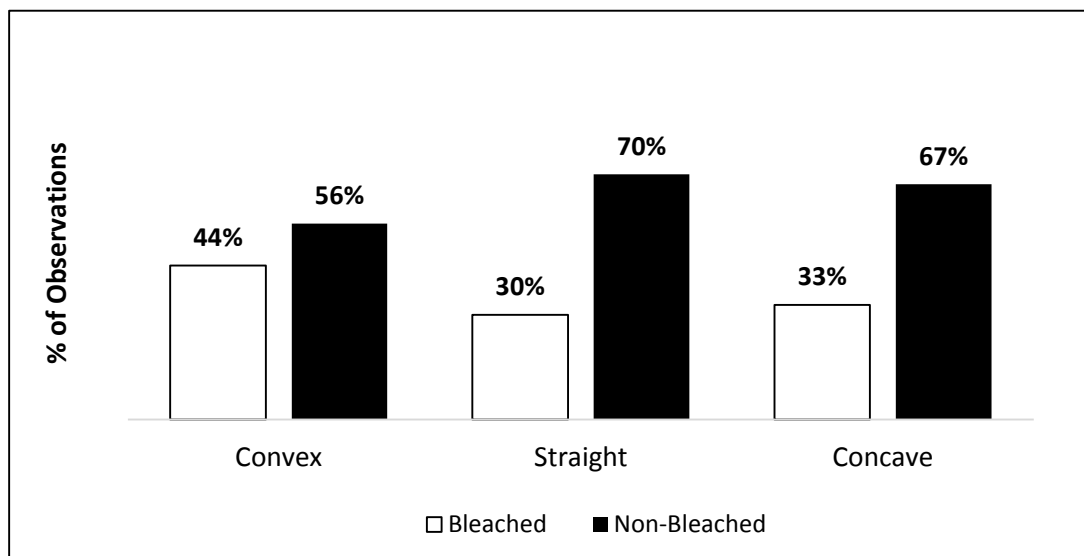


Figure 5.5: Frequency of topsoil bleaching on different slope shapes (p-value < 0.01).

Topsoil bleaching showed no significant differences ($p = 0.06$) in terms of slope angle (Figure 5.6). Despite the results not being significant at the 95% confidence level, it does show a trend that topsoil bleaching is highest at steeper slope angles, which is consistent with the findings of van Tol et. al. (2013). Van Tol et. al. (2013) examined the importance of interflow in E horizons from 320 soil profiles selected from the Land Type Database and concluded that higher occurrences of bleaching taking place at steeper angles. A study performed by Van der Waals (2013) on soil colour variation between topsoil and subsoil horizons in a plinthic catena on the Mpumalanga Highveld also reported the high occurrence of bleaching on steeper slope angles. Steeper slope angles are commonly associated with midslope positions (van Tol et. al., 2013) which is also where the highest occurrence of bleaching was observed for this study (Figure 5.4).

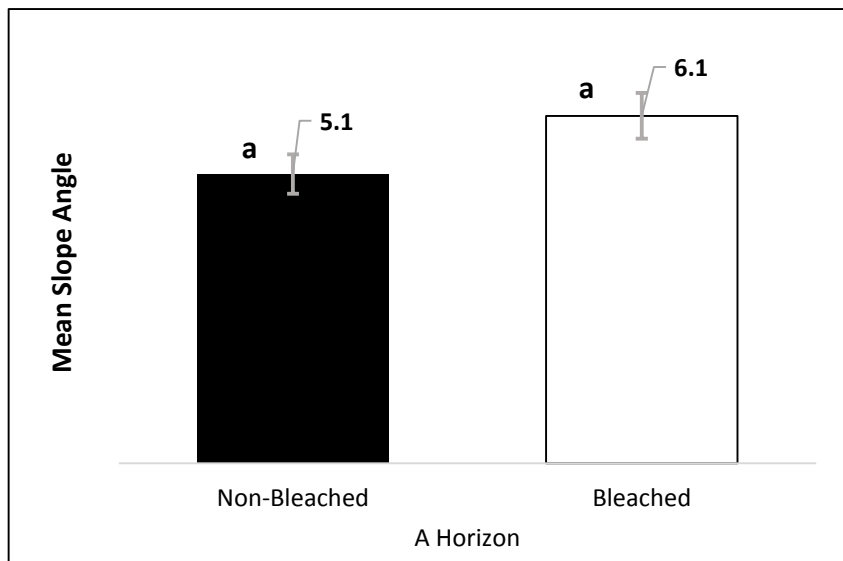


Figure 5.6: Mean slope angle as a function of bleached and non-bleached A horizons. Error bars indicate the standard error. Same letters above bars indicate no significant difference at the $p < 0.05$ significance level (p -value = 0.06).

Bleaching occurrences on the various slope aspects were also investigated, but no significant differences were observed ($p = 0.63$). Results are shown in Appendix 3, Figure A3.1.

From the above results it is clear that no distinct landscape pattern could be assigned to the occurrence of bleaching. The results obtained for one landscape property contradicts the results of another which might indicate the subjective nature of the geomorphic assignments in the profile database.

5.6.4 The occurrence of bleaching in relation to parent material

The CPSD %, used as a measure of LD's, is given in Figure 5.7. The presence of an E horizon is often associated with LD's within the profile (Fey, 2010). Fey (2010) draws parallels between bleached topsoils and E horizons, describing bleached topsoils as being a weaker expression of an E horizon. Thus it is important to establish if bleached topsoils on weakly structured subsoils are also related to LD's. The data in Figure 5.7 indicates that there is no significant difference between the CPSD % of the bleached and non-bleached topsoils and thus for the current data set there is no proof that bleached topsoils on apedal subsoils are related to binary profiles.

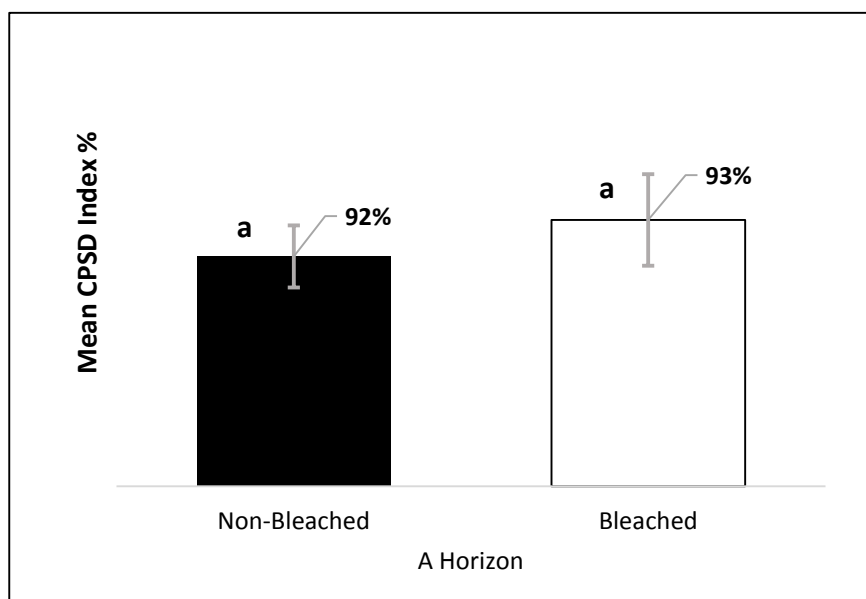


Figure 5.7: Mean CPSD % as a function of bleached and non-bleached A horizons. Error bars indicate the standard error. Same letters above bars indicate no significant difference at the $p < 0.05$ significance level (p -value = 0.50).

Figure 5.8 shows the occurrence of topsoil bleaching on the various types of parent materials. The frequency of bleaching of topsoil is significantly different ($p < 0.01$) of soil derived from the different lithologies. Topsoil bleaching occurs primarily in soils of siliceous origin. Soils of a siliceous sandstone showed the highest occurrence of bleaching (58%), followed by soil of shale (54%) and feldspathic sandstone (51%). Soils from Fe rich parent materials (mafic and dolomitic) showed the lowest occurrence of topsoil bleaching. Research performed by Van der Waals (2013), van Huyssteen et. al. (2009), van Huyssteen et. al. (1997) and Peterschmitt, et. al. (1996) also reported topsoil bleaching to occur on soils of siliceous origin, which included sandstones, shales and mudstones. This demonstrates the role of soil Fe as pigmenting agent in bleaching of soil materials. Soils that have low Fe contents such as those formed from siliceous parent materials, will expose their bleached silicate mineral content easier than soils containing high amounts of Fe. According to Torrent and Barrón (1993) and Sánchez-Marañón et. al. (1997) particle size will also influence the colour of soils. Siliceous parent materials in South Africa are mainly dominated by quartz, feldspar and phyllosilicate clays. Quartz and feldspar usually make up the bulk of the sand fractions, illites and kaolinites being the main minerals in the clay fraction (Fey, 2010). Sánchez-Marañón et. al. (1997) reported from their research on soils from carbonated sedimentary rocks in the Mediterranean, that sand was significantly negatively correlated with OC and Fe, whereas clay was positively correlated. Sand has a lower surface area compared to clay, allowing a lower amount of Fe to cover the surface of coarser grains (Gunal et. al., 2008). This would explain why coarse textured soils

will more easily expose its bleached colour when the low Fe content is being removed compared to the finer textures of soil containing a higher amount of Fe. This means that when Fe poor and Fe rich soils are exposed to the same amount of Fe loss, Fe poor soils may become bleached, where the Fe rich soils will still contain sufficient Fe to be considered non-bleached (Soileau & McCracken, 1967).

Many mafic and dolomitic rich soils contain high amounts of Mn. Although the role of Mn in the bleaching process could not be included in this study (no data available), its influence on the Fe content of soils should be mentioned. According to Dowding and Fey (2007), high manganese contents increase the redox poise of the soil, preventing organically fuelled reductive dissolution of Fe, resulting in a low degree of Fe reduction. This elevated Mn together with the higher Fe content may explain the low occurrences of topsoil bleaching in basic igneous and dolomite derived soils.

Figure 5.9 shows the spatial distribution of soils with various types of parent materials. Important to notice is the excessive amount of siliceous parent materials across South Africa. This leads one to expect bleaching to occur over a wide geographical area. Soils within the Fe rich regions would then show no or limited occurrences of bleaching. Regions showing the highest amount of siliceous profiles occur within the Cape Supergroup (mainly Western Cape and parts of Eastern Cape), Cape Granite Suite (Western Cape) and the Karoo Supergroup (parts of Western, Eastern and Northern Cape, Free State, KwaZulu-Natal and Mpumalanga). These groups are dominated by sandstones, shales and granites which corresponds with the results in Figure 5.8. Mafic parent materials dominating the coastal metamorphic regions of KwaZulu-Natal and the Eastern Cape and also in the Fe rich formations in the Lowveld. Dolomitic parent materials occurred within the Transvaal Supergroup surrounding the Bushveld Complex in the Mpumalanga, Limpopo and North West regions. The occurrence of Fe rich parent materials in predominantly siliceous regions, specifically the Karoo Supergroup, is due to the Karoo Dolerite Suite that formed a network of basic igneous sheets, dykes and sills along the floor of the basin that can be currently identified as dolerite outcrops in the landscape (Chevallier and Woodford, 1999).

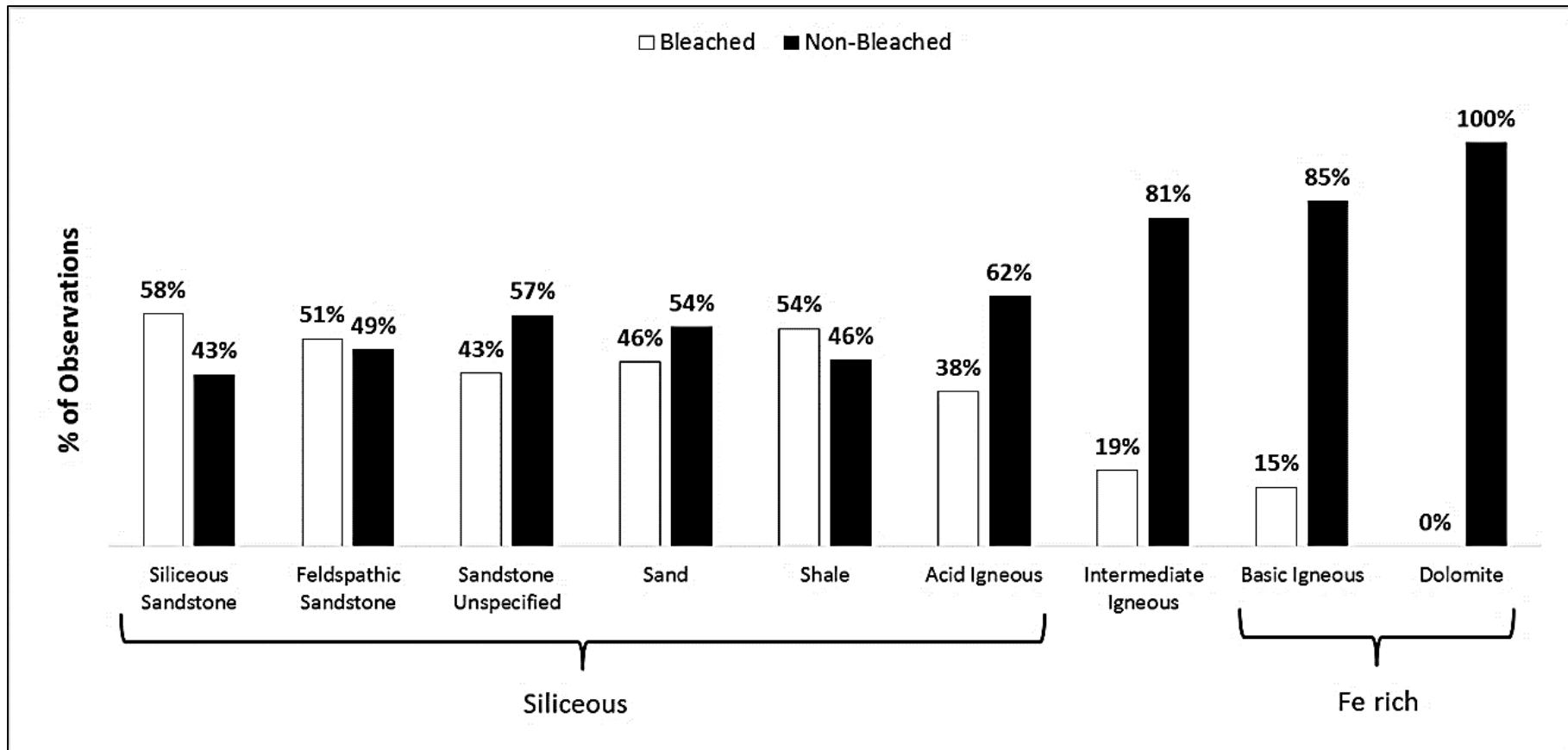


Figure 5.8: Frequency of topsoil bleaching occurring on different lithologies. The various lithologies are categorized into three main groups based on the parent materials mineral composition. The groups being of siliceous, intermediate igneous and iron rich origin, respectively (p-value < 0.01).

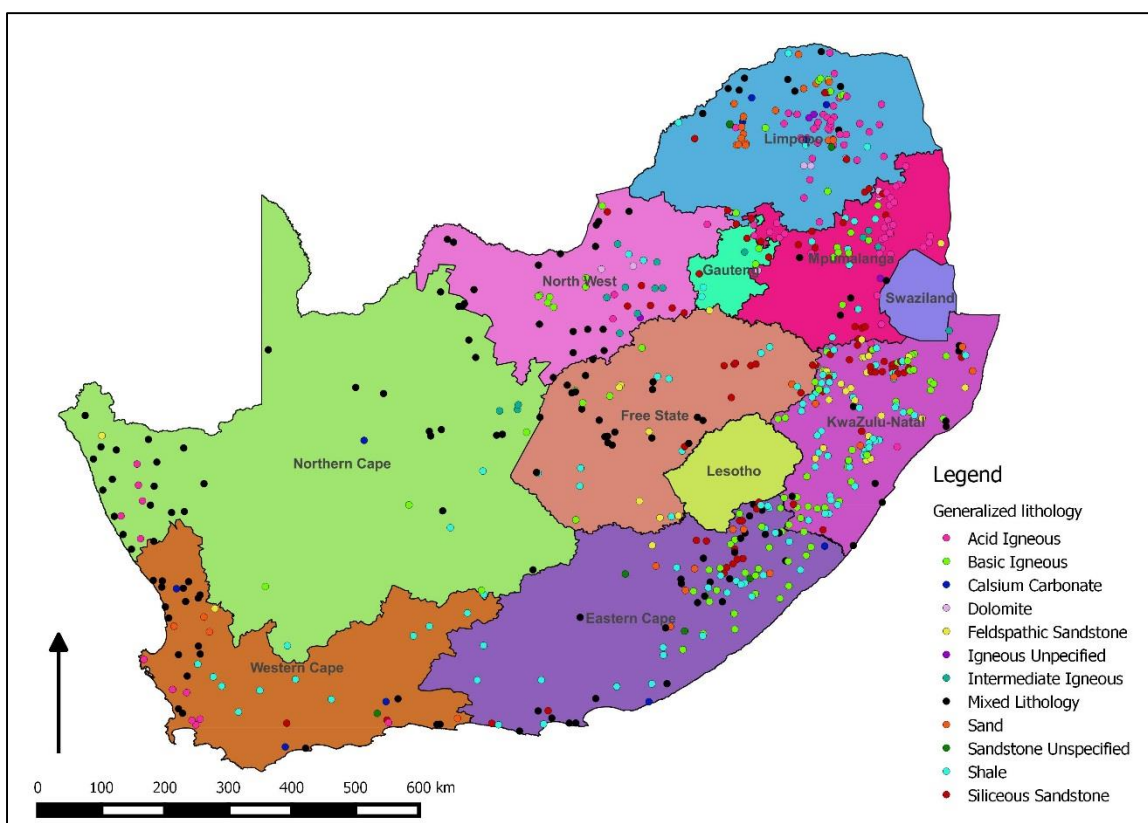


Figure 5.9: The spatial distribution of soil profiles across South Africa having various generalized lithologies.

5.6.5 Relationships between soil chemical and physical properties and the occurrence of topsoil bleaching

Soil colour can be influenced by numerous soil chemical properties (Gunal et. al., 2008). The occurrence of topsoil bleaching in soils with certain chemical properties was investigated by constructing categorized histograms and bar graphs (Figure 5.10 - 5.17).

In the South African soil classification system base status is used to indicate the degree of leaching in red and yellow-brown apedal soils (Soil Classification Working Group, 1991). Three categories are defined: eutrophic, mesotrophic and dystrophic. Soils are classified into these groups based on the S-value normalised to clay content. Figure 5.10 shows the occurrence of topsoil bleaching in each of these classes. There was a significant difference ($p = 0.02$) in the occurrence of bleaching within the three groups. Subsoils underlying bleached A horizons were predominantly dystrophic (44%), with lower occurrences of mesotrophic subsoils (37%). Subsoils underlying non-bleached topsoils were predominantly eutrophic (30%). These findings can be substantiated from the results in Figure 5.11, where bleached profiles showed a significantly ($p < 0.01$) lower base status than non-bleached soils.

Since base status and the S-value are linked to the degree of leaching in a profile (Fey and Donkin, 1994), dystrophic subsoils would be expected for well-drained soils in high rainfall regions (lower S-value). From the profiles geographical data dystrophic and mesotrophic soils dominate the eastern regions of South Africa and also parts of the West Coast region. The occurrence of dystrophic profiles in the eastern regions of the country would be expected since these regions receive the highest annual rainfall, which will promote leaching. Eutrophic profiles mainly occurred in the central and western parts of South Africa where rainfall is typically low (higher S-value). These drier regions would typically have drier soil profiles resulting in less Fe reduction. Calcium (Ca^{2+}) may have been the dominant cation in Eutrophic soils, which would have stabilised the clay, ultimately preventing illuviation (Fey, 2010).

Another factor which may explain the high occurrence of bleached topsoils on dystrophic subsoils, is soil acidity. Dystrophic soils are usually acidic (Fey, 2010). Soils at low pH tend to experience reduction at higher Eh conditions than higher pH soils. Thus it may be redox drivers that result in acidic dystrophic soils being more prone to bleaching.

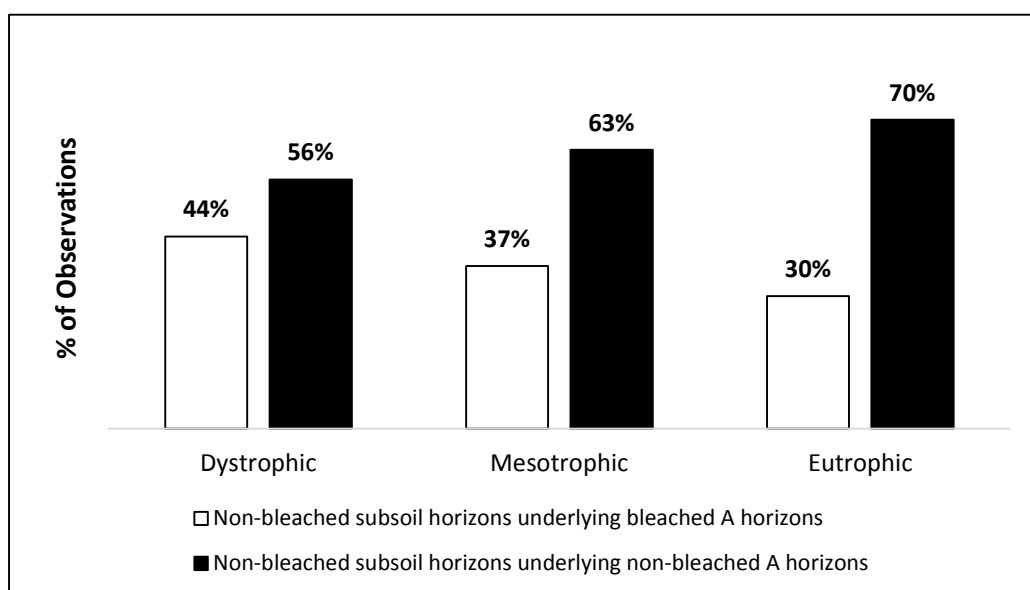


Figure 5.10: Frequency of bleaching and non-bleached topsoils on subsoils showing different base statuses (p-value = 0.02).

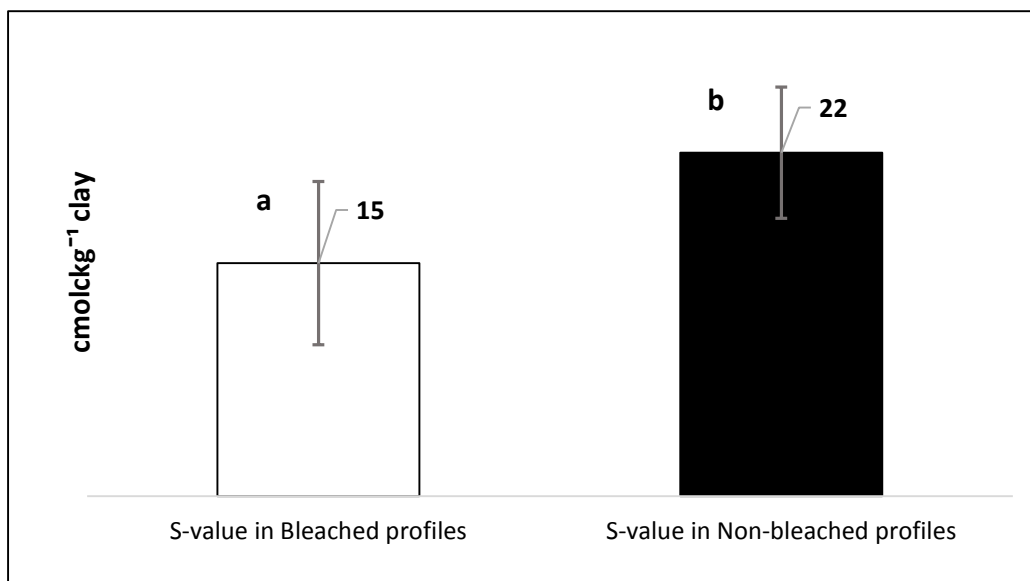


Figure 5.11: Mean S-value in bleached and non-bleached B horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level ($p\text{-value} < 0.01$).

The occurrence of topsoil bleaching on subsoils with luvic and non-luvic properties is shown in Figure 5.12. No significant differences ($p = 0.49$) were observed between bleached topsoils occurring on luvic and non-luvic subsoils. Thus for the current data set there is no proof that apedal subsoils underlying bleached topsoils will show luvic properties.

These results were not expected since from our current understanding of bleaching, clay usually becomes unstable in the absence of Fe causing clay to be illuviated into the subsoil (Soil Classification System, 1991). Van der Waals (2013) performed a study on soil colour variation between topsoil and subsoil horizons in a plinthic catena on the Mpumalanga Highveld. From his study's results it was observed that bleached topsoils had a sandier texture than the underlying subsoil. Since the criteria was met for a profile to qualify as being luvic, most yellow-brown apedal profiles in the study showed to be luvic. Van der Waals (2013) postulated that the luvic nature of these profiles could possibly have led to increased Fe reduction in the A horizon due to water ponding after rainfall events causing bleaching. Even the slightest difference in texture between the topsoil and subsoil can cause the build-up of a perched water table within the topsoil during high rainfall events, causing reduction and luviation of clay (van Tol, 2013). It is clear that the results from this data set do not support this theory of van Tol (2013) on clay luviation.

According to le Roux (2015) who studied the occurrence of bleached topsoils on apedal subsoils of the Western Cape and Mpumalanga provinces, bleached topsoils in the Western Cape tended to be more dispersive than the non-bleached topsoils. Despite this however, clay

dispersion as main cause of topsoil bleaching could not be proven. In the Mpumalanga profiles, bleached topsoils were not shown to be dispersive and here reduction was more likely the process responsible for topsoil bleaching. From the data presented in this chapter, bleaching mainly occurred on siliceous parent materials, such as sandstone and sand (Figure 5.8). These parent materials which are usually associated with low clay contents (Fey, 2010), suggests that Fe reduction may have taken place in the topsoils but also because the inherent clay content of the soils were insufficient to develop a luvisc subsoil horizon.

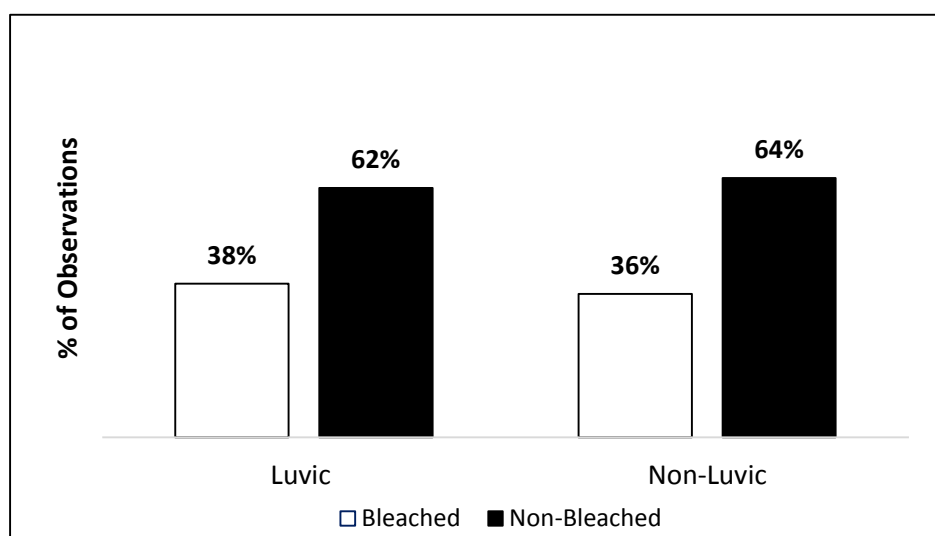


Figure 5.12: Frequency of topsoil bleaching on subsoils showing luvisc and non-luvisc properties (p -value = 0.49).

The mean CBD Fe % in bleached and non-bleached topsoils and their underlying subsoils are shown in Figure 5.13 and 5.14, respectively. These results show that non-bleached topsoils and their associated subsoils have significantly ($p < 0.01$) higher Fe contents than bleached topsoils and their associated subsoils. These results were expected and may indicate that i) soil profiles with inherently low Fe contents (from parent materials) favour the formation of bleached topsoils and/or, ii) the process of Fe loss through reduction in these soils have caused bleaching to occur in the profiles resulting in a lower Fe content. From the available data it is not possible to say with certainty what the exact reasons are, but the fact that both subsoil and topsoil Fe contents are lower in the bleached profiles, may indicate that the difference is related to initial Fe contents in the parent material. It should now be clear that Fe plays two important roles in terms of bleaching, which include: i.) Fe being a pigmenting agent, ii.) it stabilizes clay movement in soils (Sánchez-Marañón et. al., 2004). Soils with high Fe contents will thus be more stable in terms of Fe loss caused by reduction and clay dispersion.

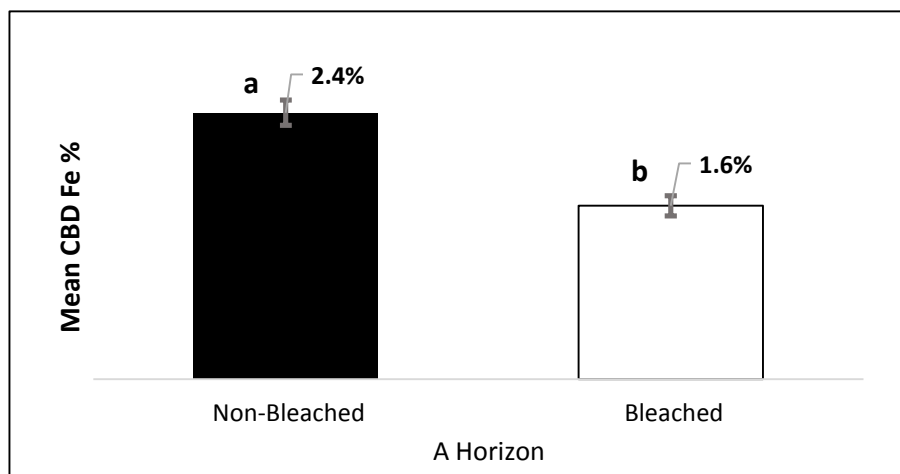


Figure 5.13: Mean CBD Fe % in bleached and non-bleached A horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value < 0.01).

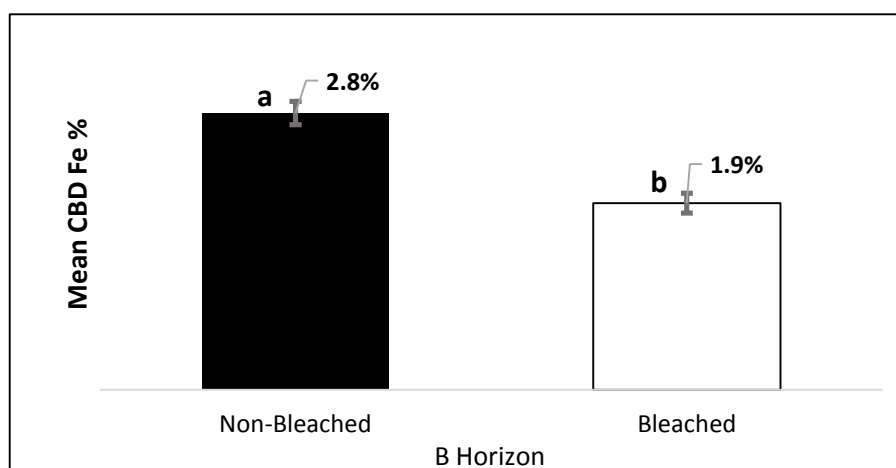


Figure 5.14: Mean CBD Fe % in subsoils underlying bleached and non-bleached A horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value < 0.01).

The mean ESP in bleached and non-bleached topsoils and their underlying subsoils is shown in Figure 5.15 and 5.16. Sodium is considered to be a highly dispersive agent that directly enhances the breakup of aggregates, especially when the Fe and SOM content in soils are low (van Zijl et al, 2014). According to Ellis (1984) the dispersive nature of bleached topsoils is often associated with crusting, surface sealing, physical instability and low hydraulic conductivity making these topsoils more prone to erosion. No significant differences were observed for the ESP in bleached and non-bleached topsoils (Figure 5.15) ($p = 0.83$) or

subsoils (Figure 5.16) ($p = 0.50$). These results do not provide evidence that Na induced dispersion is a major mechanism of topsoil bleaching.

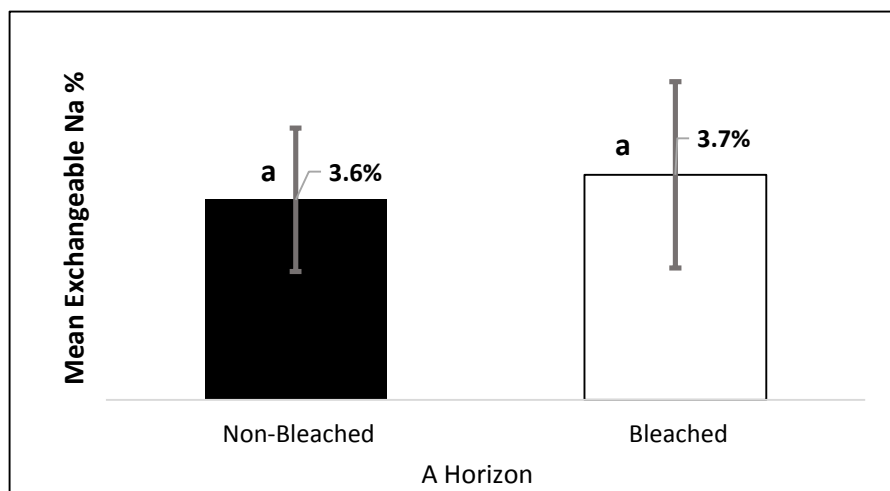


Figure 5.15: Mean exchangeable Na % in bleached and non-bleached A horizons. The error bars indicate standard error. Same letters above bars indicate no significant difference at the $p < 0.05$ significance level (p -value = 0.83).

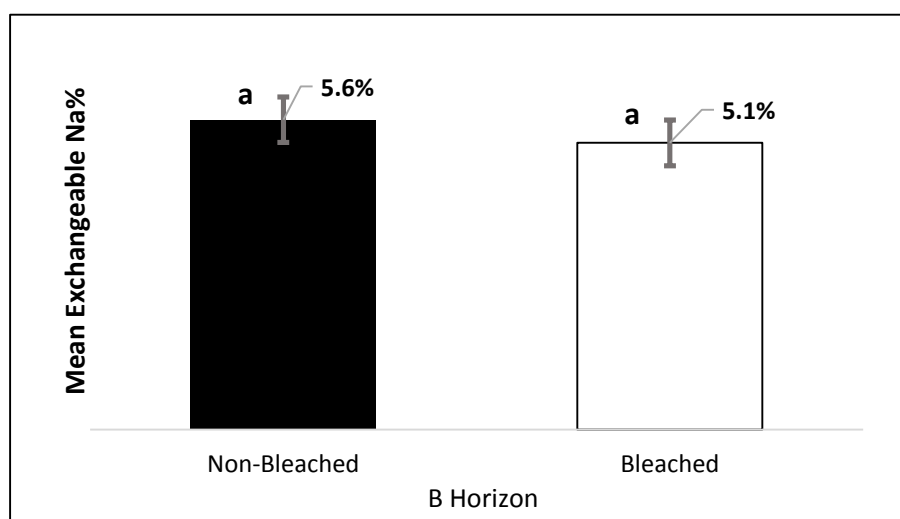


Figure 5.16: Mean exchangeable Na % in subsoils underlying bleached and non-bleached A horizons. The error bars indicate standard error. Same letters above bars indicate no significant difference at the $p < 0.05$ significance level (p -value = 0.50)

Figure 5.17 and 5.18 shows the mean EMP in bleached and non-bleached topsoils and their underlying subsoils. The EMP's of bleached topsoils and their underlying subsoils were significantly lower ($p < 0.01$) (Figure 5.17) than the non-bleached topsoils and underlying subsoils. This again, does not support the hypothesis of clay dispersion as the sole

mechanism of bleaching. The role of Mg on clay dispersion is less understood than the role of Na, and often depends on the clay mineralogy of the soil (Rahman & Rowell, 1979). However, it has been shown that exchangeable Mg can promote clay dispersion indirectly by enhancing the effect of Na on soil dispersion (Rengasamy et. al. 1986), with Mg often decreasing the ESP required to cause dispersion (Emerson & Bakker, 1973). If a dispersive mechanism were to be responsible for topsoil bleaching one may expect bleached profiles to have a higher EMP than non-bleached profiles. However, the current data shows the opposite trend with non-bleached soils having a significantly higher EMP than the bleached soils. A possible explanation for the higher exchangeable Mg in non-bleached soils may relate to the lithological control on bleaching. Soils derived from mafic and dolomitic rocks show the least occurrences of bleaching (Figure 5.8). From Figure 5.19 and Figure 5.20 it is clear that these mafic/dolomitic parent materials contain significantly ($p < 0.01$) higher EMP in the topsoil and subsoil compared to the more siliceous parent materials. For these high Fe/Mg soils, Fe might create a stabilized environment for clay and will dominate over the dispersive nature of Mg.

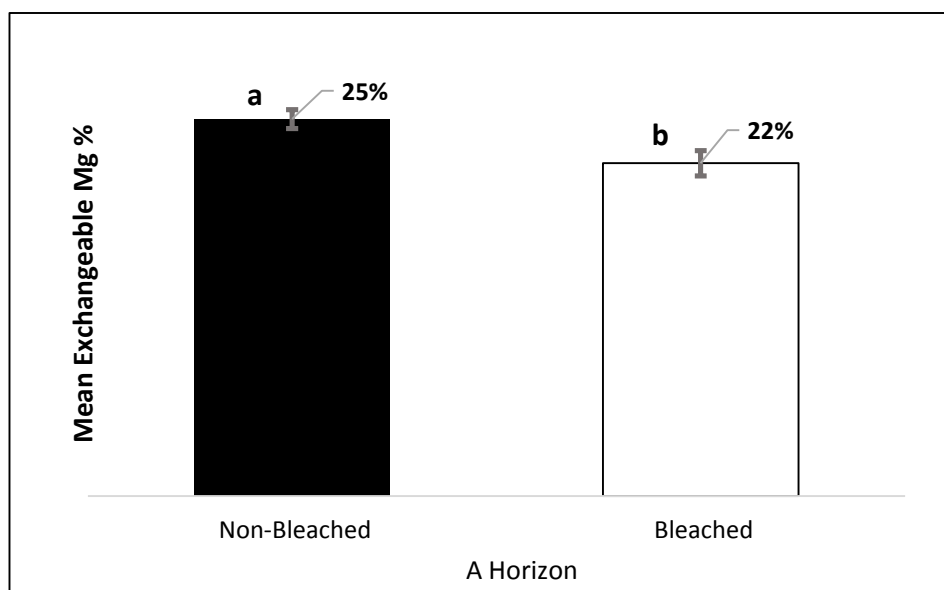


Figure 5.17: Mean exchangeable Mg % in bleached and non-bleached A horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value < 0.01).

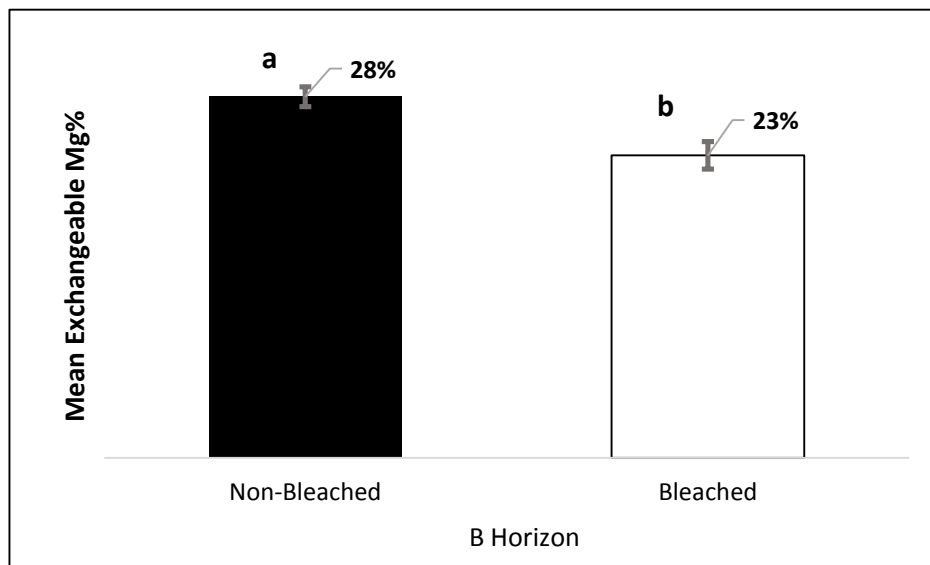


Figure 5.18: Mean exchangeable Mg % in subsoils underlying bleached and non-bleached A horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value < 0.01).

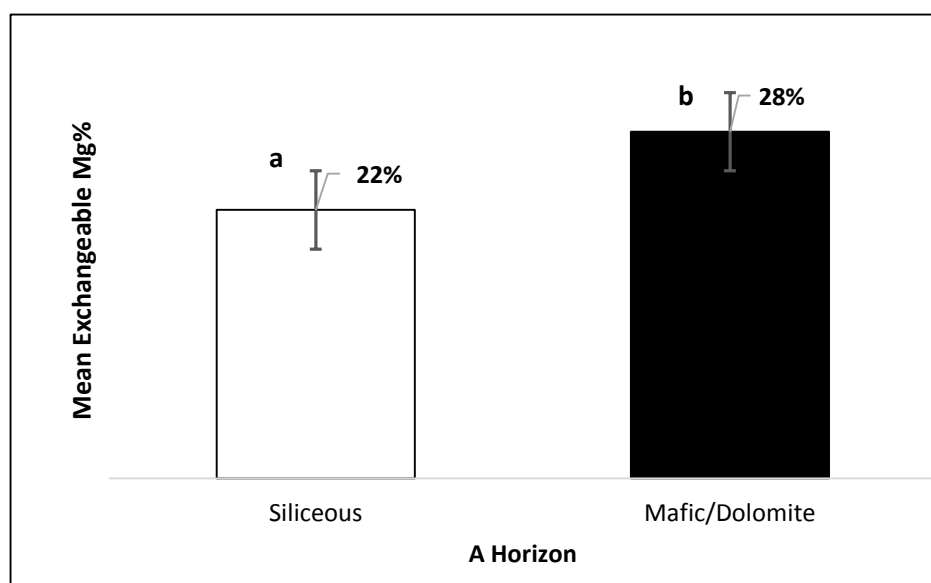


Figure 5.19: Mean exchangeable Mg % in A horizons derived from siliceous and mafic/dolomitic parent materials. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value < 0.01).

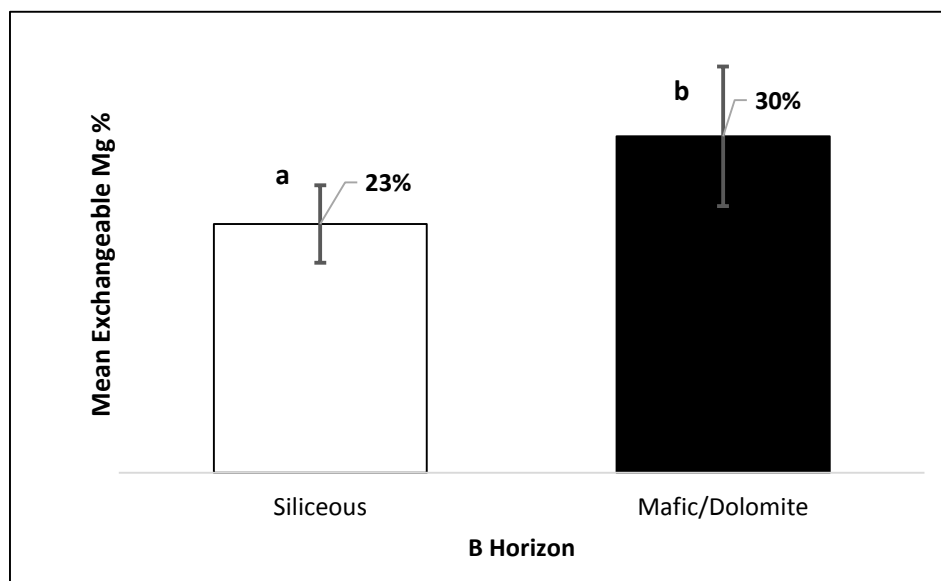


Figure 5.20: Mean exchangeable Mg % in B horizons derived from siliceous and mafic/dolomitic parent materials. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value < 0.01).

Figure 5.21 and 5.22 shows the mean OC% in bleached and non-bleached topsoils and their underlying subsoils. No significant differences were observed for the OC% in bleached and non-bleached topsoils (Figure 5.21) ($p = 0.41$) or subsoils (Figure 5.22) ($p = 0.29$).

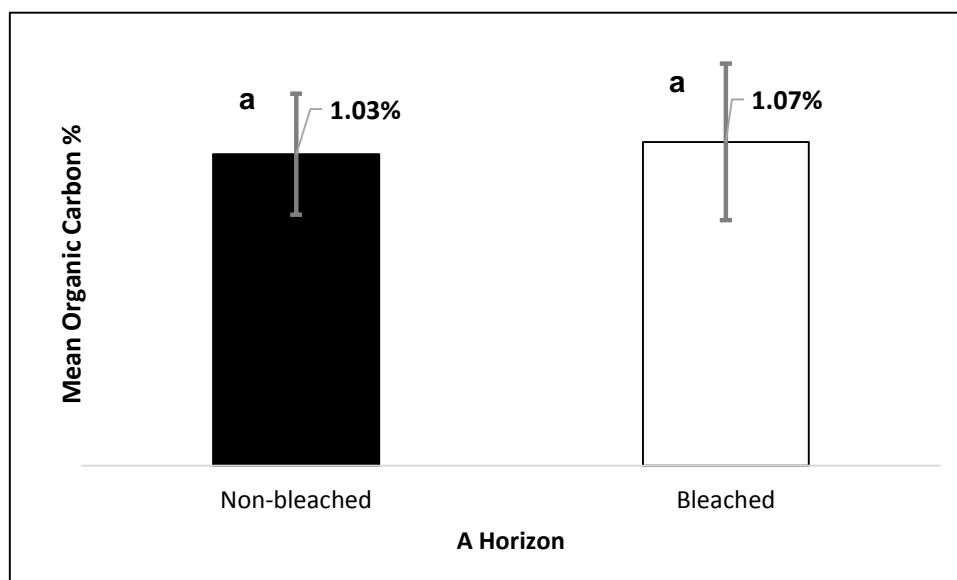


Figure 5.21: Mean organic carbon % in bleached and non-bleached A horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value = 0.41).

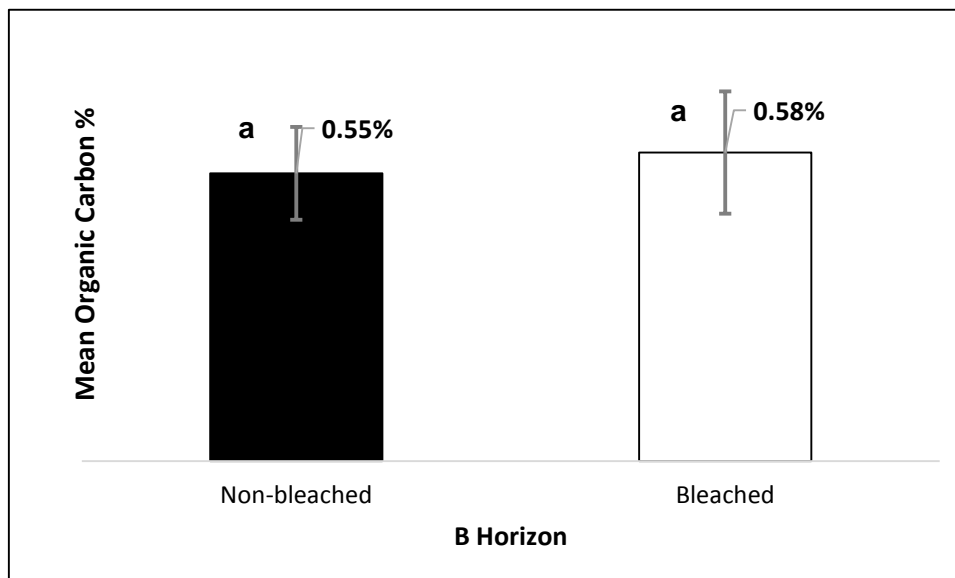


Figure 5.22: Mean organic carbon % in subsoils underlying bleached and non-bleached A horizons. The error bars indicate standard error. Different letters above bars indicate a significant difference at the $p < 0.05$ significance level (p -value = 0.29).

5.6.3 Occurrence of topsoil bleaching on different apedal subsoil horizons and soil forms.

From the spectroscopic colour data, the frequency of topsoil bleaching was determined on the different apedal B horizons and on the different soil forms by constructing categorized histograms. The results in Figure 5.23 shows topsoil bleaching primarily occurred on yellow-brown apedal B horizons (66%). Red apedal B horizons showed the lowest occurrence of topsoil bleaching (19%). Results for topsoil bleaching on neocutanic subsoils are less reliable than the results of red and yellow-brown subsoils since they only represent 19 profiles in the data set, where red and yellow-brown subsoils represent 435 and 267 profiles, respectively. From the results in Figure 5.23, the highest occurrence of topsoil bleaching occurred in Avalon soils (yellow-brown apedal B horizon) (79%) and the lowest in Hutton soils (red apedal B horizon) (18%). Oakleaf soils (neocutanic B) showed 58% occurrences of topsoil bleaching.

Hematite that forms in well-drained, stable environments (Schwertmann, 1993), is responsible for the red colour in apedal B horizons. The formation of yellow-brown subsoils are generally associated with cooler, moister conditions, where goethite is primarily responsible for the soils colour. According to Wheeler et. al. (1999) who studied the redox conditions between red and brown soils from high Fe containing parent materials in Minnesota, goethite is considered to be the product of organically-fuelled, redox depletion of hematite in soils that contains both hematite and goethite. The more stable goethite will remain after hematite is removed through

leaching. This preferential reduction of hematite is seen as being diagnostic of hydromorphic conditions (Fey & Manson, 2004). Oxygen and organic substrates in the A and yellow-brown apedal B subsoil horizons available for bacterial reduction of mainly hematite, will ultimately be leached to the underlying horizon, forming a red apedal subsoil (Fey, 2010). Although this might be true, goethite do not necessarily need to develop from hematite. It can also develop due to a lower Fe content in the soil, or that the formation of hematite is not favoured because of different climatic and landscape conditions (Schwertmann, 1994).

The high occurrences of bleaching on yellow-brown apedal subsoils is a very important finding. This means 66% of topsoils occurring on yellow-brown apedal subsoils are bleached and cannot be classified accordingly since bleaching is not recognized on well-drained yellow-brown apedal subsoils (Soil Classification Working Group, 1991). The low frequencies of topsoil bleaching on red apedal B horizons are expected, since these soils usually occur in very well-drained conditions where Fe is stable and reduction is limited (Fey, 2010). Whether reduction or clay dispersion is responsible for bleaching in these red apedal profiles is not clear. According to Fey (2010) and van Huyssteen et. al. (1997) differences in soil colour (due to reduction) may be due to different degrees of wetness within horizons. Van Huyssteen et. al., (1997) conducted a study on soils of the Grabouw district where they developed an equation to relate the duration of wetness to the colour of red and yellow-brown apedal B and E horizons. From the results they reported an increase in water duration for these subsoils in the order: red apedal B < yellow-brown apedal B < E horizon. Similarly, Van der Waals (2013) who studied the colour variation between topsoils and subsoils in a plinthic catena on the Mpumalanga Highveld, reported bleaching in topsoils overlying yellow-brown apedal subsoils. He stated that these bleached topsoils exhibited lower chroma and value than the subsoils. These bleached topsoils also approached the chroma found in many A horizons overlying E horizons. It was then suggested that the water regime causing the formation of bleached A horizons on E horizons were similar to the water regime causing topsoil bleaching on yellow-brown apedal B horizons.

Topsoil bleaching on neocutanic subsoils was expected. These soils are also considered to be well-drained, and are often associated with footslopes and valley bottom positions (Soil Classification Working Group, 1991). Van der Waals (2013) suggested that bleached topsoils overlying neocutanic subsoils formed due to clay illuviation, giving the soil its neocutanic character. Although clay illuviation might be a good explanation for the formation of bleached topsoils in neocutanic profiles, bleaching due to reduction might also be possible. According to Fey (2010) clay movement in cutanic soils may not necessarily reflect periodically saturated conditions in soils, but can also develop as a result of the initial stages of podzol B formation or eluviation of clay with OM.

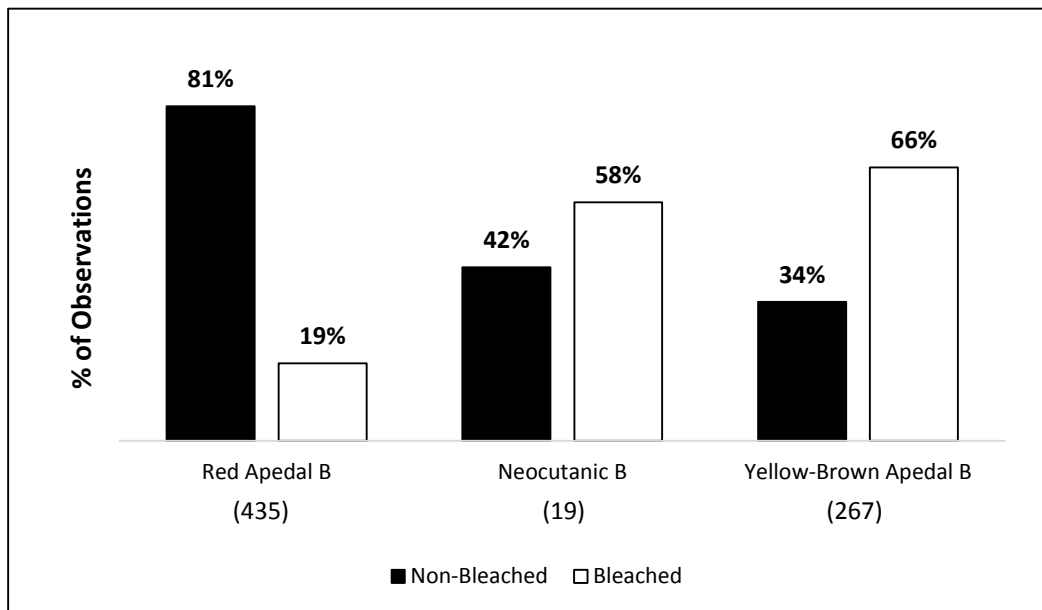


Figure 5.23: The frequency of bleached A horizons on apedal and neocutanic B horizons. The number of soil profiles representing each diagnostic subsoil in data set are given in brackets.

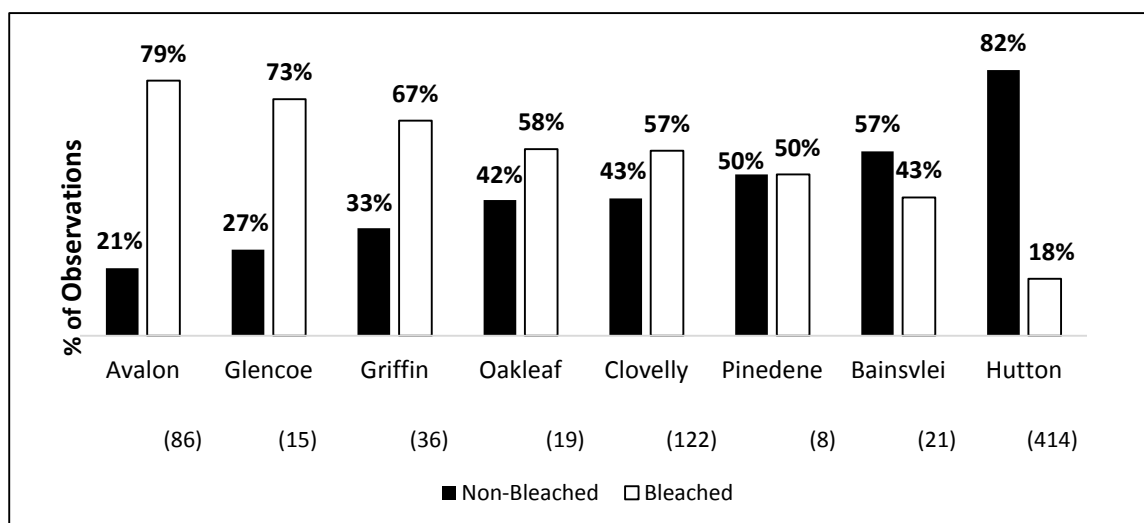


Figure 5.24: Frequency of bleached A horizons in soil forms containing apedal B horizons. Bleached A horizons were determined from spectrophotometer colour measurements. The number of soil profiles representing each soil form in data set are given brackets.

From Figure 5.24, Avalon and Glencoe soils have shown the highest occurrences of topsoil bleaching. These soils contain yellow-brown apedal B horizons that overly plinthic horizons. These plinthic horizons usually signifies a fluctuating water table within the plinthic zone which in periods of high rainfall can cause water to build up in the soils overlying it (Fey, 2010). Generally, soils containing plinthic materials are wetter than soils not containing plinthic

materials. This means the probability of bleached topsoils forming in these soils would be higher than for soils not containing plinthic materials. Almost 80% of all Avalon soils in the data set seems to have a bleached topsoil (Figure 5.24). There seems to be no great difference in the occurrence of topsoil bleaching in soils containing yellow-brown apedal subsoils that overly soft (Avalon) or hard (Glencoe) plinthic materials. The low occurrence of Glencoe soils (15 profiles) compared to Avalon soils (86 profiles) in the data set may cause these results to be unreliable.

The occurrence of topsoil bleaching in Griffin soils is rather interesting and can be explained by the preferential reduction of hematite (Wheeler et al, 1999) as was explained in the previous section. Although not shown in this chapter, Griffin soils were mainly located in KwaZulu-Natal and Mpumalanga where the climatic conditions (high temperatures and summer rainfall) would be ideal for the formation of these soils. Interestingly the profile picture for the Griffin form in the South African Soil Classification System handbook illustrates a typical Griffin soil that contains a bleached A horizon (Soil Classification Working Group, 1991). The higher occurrence of topsoil bleaching in Griffin soils (67%) compared to Oakleaf (58%), Clovelly (57%) and Pinedene (50%) soils is not clear.

The higher occurrence of bleaching in Oakleaf and Clovelly soils compared to Pinedene soils is unusual (Figure 5.24). This is because the unspecified materials underlying the yellow-brown apedal B horizon in Pinedene soils are recognized by its wetness, which might lead one to think topsoil bleaching to occur more frequently in these soils. This is not the case in Clovelly and Oakleaf soils where the underlying materials in the profile should not show any signs of wetness. The low occurrence of Pinedene soils (8 profiles) in the data set can probably explain the low occurrences of topsoil bleaching compared to Clovelly and Oakleaf soils. As was mentioned before, majority of these soils were classified with the previous edition of the South African Soil Classification handbook (1977) that did not recognise signs of wetness in soils containing neocutanic subsoils. This criteria was updated in the current edition of the Soil Classification Systems (Soil Classification Working Group, 1991). The Tukulu soil form was added to the current classification system to accommodate signs of wetness in soils containing neocutanic subsoils. If this soil form was available in the previous edition of the South African Soil Classification System (1977) higher frequencies of topsoil bleaching on neocutanic subsoils may have been identified. The higher occurrence of topsoil bleaching on red apedal subsoils in Bainsvlei soils compared to Hutton soils was expected (Figure 5.24), since Bainsvlei soils contain plinthic materials that may cause these profiles to be wetter and more prone to topsoil bleaching.

Van der Waals (2013) reported from his study on the colour variation between topsoils and subsoils in a plinthic catena on the Mpumalanga Highveld that topsoil bleaching primarily occurred in Clovelly, Avalon, Pinedene and Glencoe soils. No occurrences of topsoil bleaching were reported for Hutton and Bainsvlei soils. Van Huyssteen et. al. (2010) reported from their research on the soil-water relationships of 28 soil profiles in the Weatherly catchment, Eastern Cape, South Africa, that the saturation duration in the different soil forms increased in the order: Avalon < Hutton < Pinedene. No clear explanation could be given for why Hutton (red apedal B horizon) soils were saturated for longer periods than Avalon (yellow-brown apedal B horizons) soils. Van Huyssteen et. al. (2010) also reported that the saturation duration in the subsoils of the 28 profiles studied, decreased in the order: yellow-brown apedal B > red apedal B > neocutanic B. They also found that as the saturation duration in the soils increased the terrain and soil texture also tended to change. The saturation duration generally increased from crest to valley bottom positions, with a decrease in particle size down slope. Although the occurrence of topsoil bleaching was not reported in van Huyssteen et. al. (2010) study, it can be suggested that during wetter summer months reduction processes could have been activated in topsoils overlying yellow-brown apedal subsoils due to a possible increase in water content in the A horizon. Higher temperatures during the summer rainfall months together with the presence of a higher SOM in the A horizon can create the ideal conditions for microbes to accelerate reduction processes that may result in topsoil bleaching. Research conducted by Fey (2010) on well-drained soils occurring on plinthic horizons, reported that the well-drained soils tended to increase in wetness in the order: red apedal B < yellow-brown apedal B < yellow E horizons < grey E horizons. He also suggested that increased reduction within topsoils overlying well-drained subsoils may have been caused by increased microbial activity in the topsoils due to higher SOM contents. This increase in reduction in the topsoil may then lead to the formation of bleached A horizons (Fey, 2010). One would then expect the probability of bleached topsoils to occur on yellow-brown apedal subsoils to be greater than for red apedal subsoils, due to the combined effect of longer periods of water saturation and higher OC contents in the topsoil. The highest occurrences of topsoil bleaching in Avalon and Glencoe soils also suggests that topsoil bleaching might be the result of Fe reduction caused by wetter conditions in these soils.

On a family level topsoil bleaching primarily occurred in Iuvic families (Figure 5.25). According to the texture analysis data from the data set no trend could be identified between topsoil bleaching and clay movement (Figure 5.12). Clearly there is a difference between clay estimations made in the field and in the laboratory. If the texture analysis in the data set confirmed what has been observed in the field, the well accepted theory of bleached topsoils occurring on a subsoils with higher clay content, would be supported. For Griffin soils, there

seems to be no major difference between the occurrence of topsoil bleaching on luvic and non-luvic profiles. It may be possible that reduction and clay dispersion is responsible for topsoil bleaching.

From the results in this study it appears that wetter soil forms containing yellow-brown apedal subsoils have the highest occurrences of topsoil bleaching. Evidence which supports the notion that yellow-brown apedal subsoils tend to have wetter water regimes than red apedal subsoils was provided by Van der Waals (2013), van Huyssteen et. al. (2010) and Fey (2010). It also became clear from these studies that the occurrence of bleaching might be due to a specific set of conditions or external factors together with various interacting soil properties unique to a specific geographical area. This also leads to question whether different bleaching mechanisms exist in different regions of the country and if all bleached topsoils show the same instability as those described in the Karoo by Ellis (1984). From the results in this chapter it would seem that differences in Fe content parent material in soil, play the most important role in the formation of topsoil bleaching. From a classification point of view, it would be highly recommended to consider adding topsoil bleaching as a family criteria in soils forms showing 50% or more occurrences of topsoil bleaching, or at least in soil forms containing wet subsoils. The soil forms would include Avalon, Glencoe, Griffin, Clovelly and Pinedene.

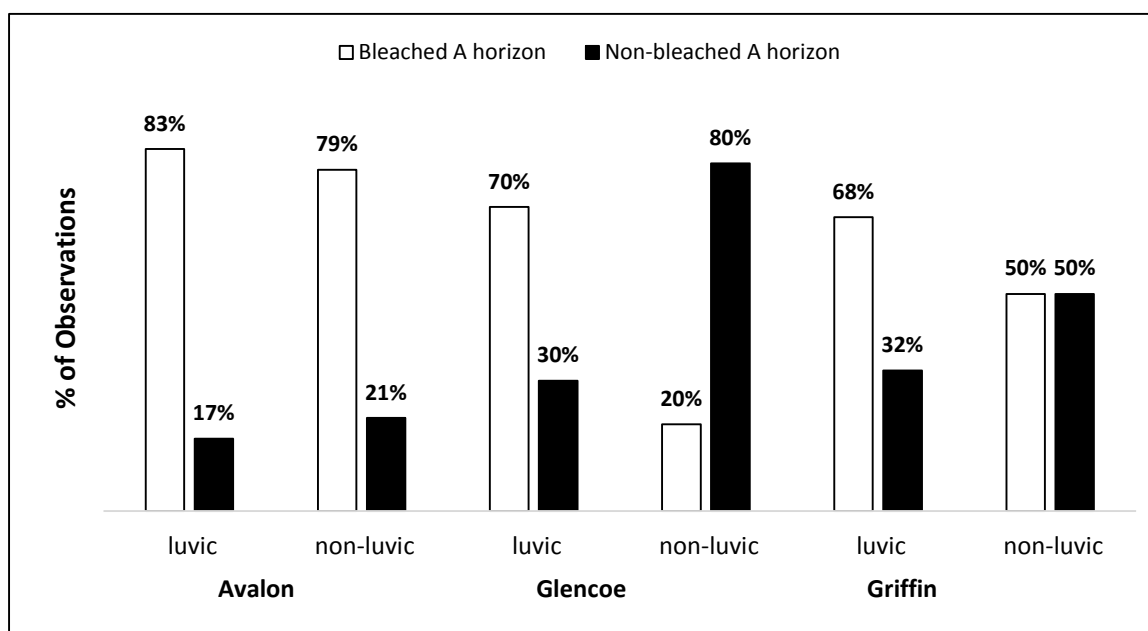


Figure 5.25: The occurrence of topsoil bleaching in luvic and non-luvic families of soil forms showing the highest occurrences of topsoil bleaching.

From the results in this study it appears that wetter soil forms containing yellow-brown apedal subsoils have the highest occurrences of topsoil bleaching. Evidence which supports the

notion that yellow-brown apedal subsoils tend to have wetter water regimes than red apedal subsoils was provided by Van der Waals (2013), van Huyssteen et. al. (2010) and Fey (2010). It also became clear from these studies that the occurrence of bleaching might be due to a specific set of conditions or external factors together with various interacting soil properties unique to a specific geographical area. This also leads to question whether different bleaching mechanisms exist in different regions of the country and if all bleached topsoils show the same instability as those described in the Karoo by Ellis (1984). From the results in this chapter it would seem that differences in Fe content parent material in soil, play the most important role in the formation of topsoil bleaching. From a classification point of view, it would be highly recommended to consider adding topsoil bleaching as a family criteria in soils forms showing 50% or more occurrences of topsoil bleaching, or at least in soil forms containing wet subsoils. The soil forms would include Avalon, Glencoe, Griffin, Clovelly and Pinedene.

5.7 Conclusion

Some results in this chapter have shown to directly contradict the current understanding of bleaching, which made the interpretation of the data challenging. Nevertheless, some important deductions could be made for bleached A horizons tending to form on well-drained red and yellow-brown apedal B horizons:

- Landscape properties showed no clear linkage with topsoil bleaching, which may be related to the subjective assignments of geomorphic properties like slope shape and landscape position.
- Lithology appears to have a strong control on topsoil bleaching, with the lowest occurrences of topsoil bleaching occurring on mafic and dolomitic parent materials.
- Bleached profiles also have a lower exchangeable magnesium percentage than non-bleached profiles, which is probably related to parent material. This could also explain the higher Fe content in non-bleached profiles, although less Fe in bleached profiles may also occur due to increased reduction in wetter profiles.
- The chemical and physical data (clay movement, exchangeable sodium percentage) does not provide much evidence for topsoil bleaching to develop due to a dispersion based mechanism.
- Both bleached and non-bleached topsoils are features in all the soil forms listed in this study.
- Topsoil bleaching occurs on 66% of all yellow-brown apedal subsoil horizons in this dataset

- Evidence that may suggest wetness to be the main control of topsoil bleaching is largely from the high proportion of Avalon and Glencoe soils in the data. These soils are most often found in wetter parts of the landscape.

The high occurrence of topsoil bleaching on yellow-brown apedal subsoils is a very important finding. This study demonstrated that bleached topsoils occur on a large proportion of yellow-brown apedal subsoils and these topsoils are not recognized and cannot be classified accordingly since no classification criteria exist for this type of horizon sequence. From Figure 23 and 24 it is also clear that bleaching occurred in all soil forms presented in this study. It is thus clear that a bleached topsoil criteria should be strongly considered in the following edition of the South African Soil Classification System. Not only for the yellow-brown apedal soil forms but also for the red apedal forms.

To confidently determine the genetic pathways required for bleached topsoils to occur on well-drained red and yellow-brown apedal subsoils, further research on the relationship between bleaching and landscape properties would also be required. Further research on bleaching in terms of soil texture could also provide important information about the physical conditions required to cause bleaching.

GENERAL CONCLUSIONS

The overall aim of this study was to use the data available in the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) – Soil Profile Information System to understand the spatial and geomorphic distribution of bleached apedal profiles as well as assess their lithological, chemical, physical, spectral and subsoil colour properties to provide clues on their genesis. Bleaching can be described as the marked in situ removal of soil colour pigments (iron oxides, silicate clay and organic matter) from a soil through the process of eluviation.

In Chapter 4 soil colour measurement methods were compared to understand the differences between visual and spectroscopically measured soil colour. An attempt was also made to correlate selected soil chemical parameters with soil colour variables. From the results in this chapter the following conclusions could be made:

- The visually determined soil colours tended to have higher chroma values when compared to the spectroscopically determined soil colours. This means that the human eye is more prone to overestimate soil chroma, making soil colour more intense or colourful compared to the corresponding spectroscopic measurements. Reasons for this phenomenon is not clear but it has been suggested to be due to the preference of the human observer to perhaps better differentiate between similar colours as they progressively become darker.
- The weak relationships observed between the various soil properties and soil colour components, could possibly be due to the large spatial spread of the soils used in this study and also the fact that soil colour expression represents much more complex interactions between chemical and physical soil components than was initially expected.

In Chapter 5 the occurrence of bleached profiles in relation to geomorphic attributes, lithology, chemical and physical soil properties was investigated. The occurrence of topsoil bleaching in relation to various subsoil types and soil forms was also investigated. Due to the wide variation of soils used in this study it was not always possible to provide definitive answers to the question of topsoil bleaching, however the following main deductions could be made:

- Lithology appears to have had the strongest influence on the occurrence of topsoil bleaching in the soils used for this study. The highest occurrence of bleached topsoils being on siliceous parent materials. The tendency for bleached topsoils to occur in soils with lower exchangeable magnesium percentage and iron content compared to non-bleached profiles is probably also related to the lithology.

- The high proportion of topsoil bleaching occurring on yellow-brown apedal subsoils that forms part of the Avalon and Glencoe soil forms, may suggest wetness to be the main control of topsoil bleaching for this study. This is because Avalon and Glencoe soils are associated with plinthic subsoil materials that develop from temporary water saturated conditions.

CONSIDERATIONS FOR SOUTH AFRICAN SOIL CLASSIFICATION SYSTEM

From the results in Chapter 5 it is clear that the possibility of bleached A horizons forming on yellow-brown apedal B horizons cannot be ignored. With a 66% chance of bleaching to occur on yellow-brown apedal subsoils, it is recommended that on a family level bleaching should be recognised. Soil forms where the recognition of topsoil bleaching on a family level should be considered, at least for the wetter variants, include the Avalon, Glencoe and Pinedene soil forms. Ideally a bleaching criteria should be considered for all the soil forms presented in this study, since topsoil bleaching was a feature in all of the relevant soil forms.

RECOMMENDATIONS

In studies where soils are researched based on their colour, the use of instrumentally determined soil colours is recommended. This will ensure accurate and consistent colour measurements providing objective results, allowing one to make unbiased conclusions. The use of visual colour measurements in these type of studies may provide subjective results especially if a certain outcome is expected. In cases where visual estimates are sufficient, more than one observer is recommended to make measurements. The relatively weak correlations observed between soil properties and soil colour components may be explained by the wide heterogeneous spread of the soils that have been studied (Ibáñez-Asensio et. al. (2013); Schulze et. al. (1993); Fernandez et. al. (1988)). When having to deal with large data sets where soils are scattered over a wide geographical area, as was the case in this study, it would be highly recommended for these large data sets to be made smaller by possibly grouping soils in terms of similar geomorphological, physical or chemical properties.

The subjective assignments of geomorphic properties like slope shape, slope angle and landscape position may have led to the indistinct relationship between landscape properties and topsoil bleaching. The use of high-resolution (<20 m) DEM's would be recommended for future studies where geomorphic properties in relation to soil genesis are being researched.

Such DEM's will deliver more accurate data on different landscape properties, because homogenous terrain units are being identified on a meso- and micro-scale by classifying and combining slope angle, aspect and slope shape (van Niekerk & Schloms, 2002). Van Tol et al. (2012) also made use of a high resolution DEM to redetermine the slope angle data provided by the Land Type Database, for their study on subsurface lateral flow in E horizons in South African soils.

FUTURE STUDIES

Studying the occurrence of topsoil bleaching on well-drained subsoils on a provincial level may provide valuable information on the processes and environmental conditions responsible for the formation of bleached topsoils in that province. Research on the occurrence of bleached topsoils overlying well-drained subsoils in terms of vegetation and various climatic factors could also prove to be insightful. Van der Waals (2013) reported from his research on the colour variations in subsoils on a plinthic catena in the Mpumalanga Highveld that yellow-brown apedal subsoils underlying bleached topsoils had the same water regime as E horizons underlying bleached topsoils. Further research on this topic, using hydrological techniques, in different locations and on different hydromorphic sequences in South Africa can only provide further evidence and reasons to recognize topsoil bleaching on well-drained apedal soils in the South African Soil Classification System (Soil Classification Working Group, 1991). The general lack of research on bleached topsoils provides numerous opportunities for future studies. Research providing new valuable information and insight on the processes driving its formation and external factors possibly influencing pedogenic processes is encouraged, not only in South Africa but also internationally.

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Appendix 1 – Supplementary data from Chapter 2

Table A1.1: Time of day visual colour measurements were performed and weather conditions for non-consecutive days of colour measurement in Stellenbosch (Western Cape).

Measuring environment	Date	Hour interval h (GMT+2)	Sky state*	Temperature °C*	Precipitation mm*
Laboratory	27 May 2014	13:30 – 16:30	Intervals of clouds and sun	11.0 - 18.0	0
Laboratory	28 May 2014	10:00 – 11:00	Rain and light precipitation	13.0 - 18.0	21
Laboratory	22 April 2015	10:30 – 14:30	Sun with intermitted clouds	13.0 - 22.0	0
Laboratory	23 April 2015	11:00 – 15:00	Sun	15.0 - 23.0	0
Field	25 April 2015	10:30 – 12:30	Overcast	12.0 - 20.0	0
Field	18 May 2015	10:30 – 13:00	Intervals of clouds and sun	11.0 - 24.0	0

(*Source: SA Weather [Online] Available: <http://www.weather.news24.com> [2015, May 27])

Appendix 2 - Supplementary data from Chapter 3

Table A2.1: Correlation matrix for 100 soil samples measured visually with and without viewing masks and spectroscopically.

Colour Variable and Condition	Hue Lab Dry	Value Lab Dry	Chroma Lab Dry	Hue Field Dry	Value Field Dry	Chroma Field Dry	Hue Lab Dry (Masks)	Value Lab Dry (Masks)	Chroma Lab Dry (Masks)	Hue Field Dry (Masks)	Value Field Dry (Masks)	Chroma Field Dry (Masks)
Hue Lab Dry	1.00			0.77			0.87			0.89		
Value Lab Dry		1.00			0.45			0.69			0.65	
Chroma Lab Dry			1.00			0.58			0.82			0.85
Hue Field Dry				1.00			0.73			0.76		
Value Field Dry					1.00			0.40			0.44	
Chroma Field Dry						1.00			0.59			0.61
Hue Lab Dry (Masks)							1.00			0.84		
Value Lab Dry (Masks)								1.00			0.79	
Chroma Lab Dry (Masks)									1.00			0.85
Hue Field Dry (Masks)										1.00		
Value Field Dry (Masks)											1.00	
Chroma Field Dry (Masks)												1.00

Table A2.2: Correlation matrix for 100 soil samples measured visually with and without viewing masks and spectroscopically.

Colour Variable and Condition	Hue Lab Moist	Value Lab Moist	Chroma Lab Moist	Hue Moist Field	Value Moist Field	Chroma Moist Field	Hue Dry Spectroscopic	Value Dry Spectroscopic	Chroma Dry Spectroscopic	Hue Moist Spectroscopic	Value Moist Spectroscopic	Chroma Moist Spectroscopic
Hue Lab Dry	0.84			0.76			0.73			0.59		
Value Lab Dry		0.63			0.41			0.56			0.21*	
Chroma Lab Dry			0.65			0.62			0.71			0.62
Hue Field Dry	0.72			0.93			0.7			0.55		
Value Field Dry		0.45			0.62			0.45			0.28	
Chroma Field Dry			0.50			0.77			0.5			0.53
Hue Lab Dry (Masks)	0.77			0.73			0.63			0.65		
Value Lab Dry (Masks)		0.52			0.46			0.61			0.20*	
Chroma Lab Dry (Masks)			0.59			0.64			0.77			0.65
Hue Field Dry (Masks)	0.83			0.74			0.78			0.62		
Value Field Dry (Masks)		0.52			0.47			0.52			0.13*	
Chroma Field Dry (Masks)			0.6			0.60			0.67			0.59
Hue Lab Moist	1.00			0.70			0.7			0.6		
Value Lab Moist		1.00			0.50			0.46			0.21*	
Chroma Lab Moist			1.00			0.59			0.57			0.56
Hue Moist Field				1.00			0.67			0.55		
Value Moist Field					1.00			0.39			0.23*	
Chroma Moist Field						1.00			0.58			0.64
Hue Dry Spectroscopic							1.00			0.51		
Value Dry Spectroscopic								1.00			0.27*	
Chroma Dry Spectroscopic									1.00			0.62
Hue Moist Spectroscopic										1.00		
Value Moist Spectroscopic											1.00	
Chroma Moist Spectroscopic												1.00

MFA Correlation circle for different visual colour measurement conditions using Munsell Hue, Value and Chroma

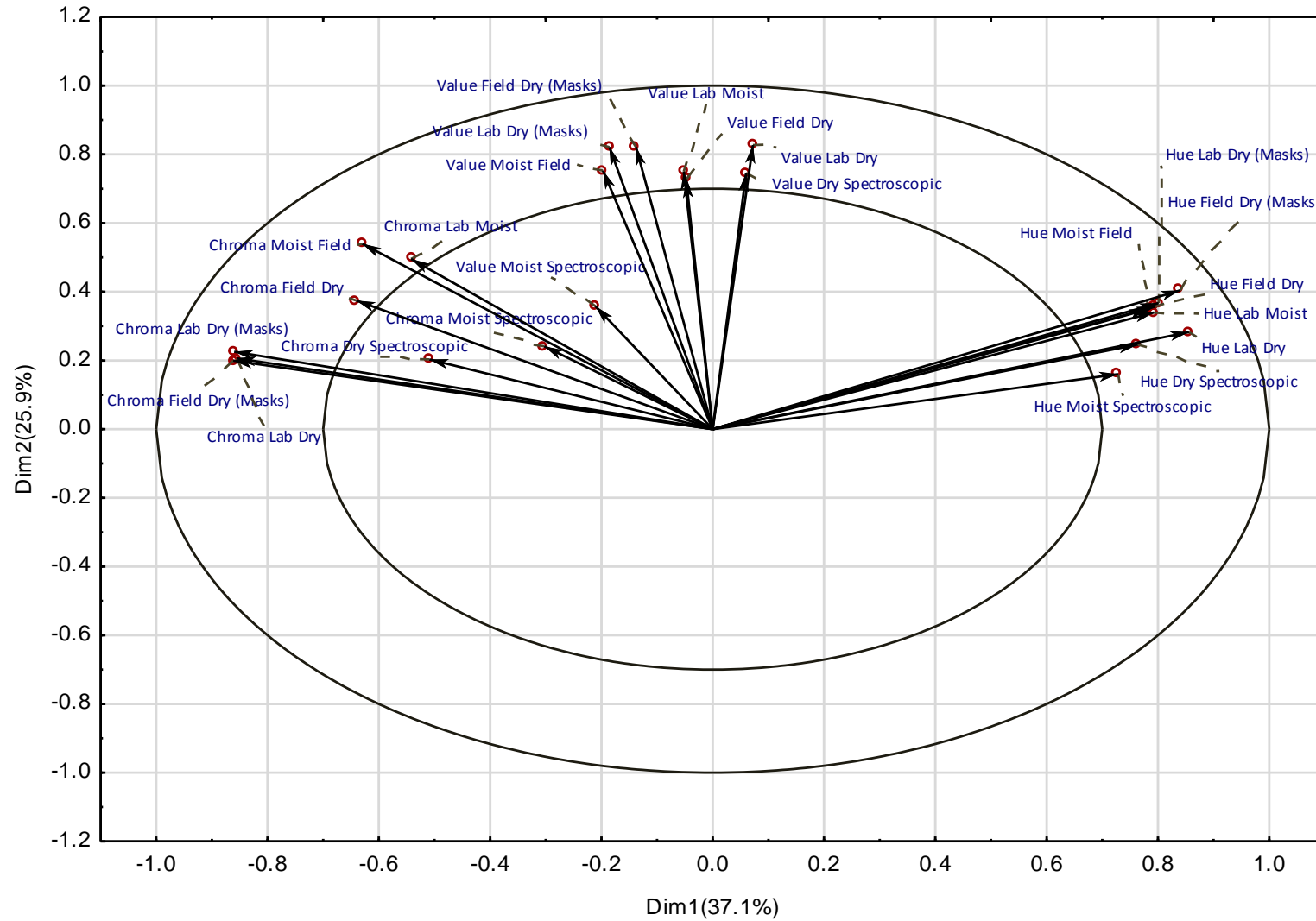


Figure A2.1: Correlation circle: relationships between colour components of different colour measurement conditions

Table A2.3: Correlation matrix: soil versus soil parameters [spectrophotometer colour measurements]

Soil property	% Organic Carbon	% Extractable Al	pH H ₂ O	CEC	ECEC (cmolc/kg soil)	Exchangeable Na (%)	Cation Na (meq/kg soil)	Cation K (meq/kg soil)	Cation Ca (meq/kg soil)	Cation Mg (meq/kg soil)	S (total cations)(cmolc/kg soil)	Exchangeable Mg (%)	% CBD Fe
% Organic Carbon	1.00	0.41	-0.50	0.70	0.12	0.04*	0.07	0.01*	-0.11	-0.02*	-0.25	-0.12	0.59
% Extractable Al		1.00	-0.74	0.31	-0.10	0.05*	-0.04*	-0.32	-0.55	-0.48	-0.66	-0.49	0.32
pH H ₂ O			1.00	-0.28	0.44	-0.07	0.20	0.39	0.68	0.51	0.84	0.32	-0.44
CEC				1.00	0.48	-0.02*	0.24	0.04*	0.17	0.34	-0.31	0.11	0.68
ECEC (cmolc/kg soil)					1.00	-0.20	0.34	0.45	0.85	0.82	0.51	0.38	0.10
Exchangeable Na (%)						1.00	0.76	-0.12	-0.25	-0.16	-0.11	-0.07	0.05
Cation Na (meq/kg soil)							1.00	0.12	0.22	0.30	0.18	0.13	0.08
Cation K (meq/kg soil)								1.00	0.48	0.38	0.45	0.10	-0.13
Cation Ca (meq/kg soil)									1.00	0.81	0.74	0.43	-0.12
Cation Mg (meq/kg soil)										1.00	0.56	0.78	0.05
S (total cations) (cmolc/kg soil)											1.00	0.34	-0.59
Exchangeable Mg (%)												1.00	0.03*
% CBD Fe													1.00

Table A2.4: Correlation matrix: soil versus soil parameters [spectrophotometer colour measurements]

Soil property	Coarse Sand %	Medium Sand %	Fine Sand %	Very Fine Sand %	Total Sand %	Coarse Silt %	Fine Silt %	Total Silt %	Clay %	UV (fiSa) - Max/Min	CPSD Index (%)	E Conductivity	Modulus of rupture	Dispersion ratio
% Organic Carbon	-0.18	-0.51	-0.55	-0.22	-0.72	0.33	0.66	0.62	0.65	0.02*	-0.16	-0.31	0.11	-0.20
% Extractable Al	-0.15	-0.24	-0.19	-0.12	-0.37	0.21	0.35	0.21	0.39	0.04*	-0.01*	-0.02*	-0.09*	-0.12*
pH H ₂ O	0.06	0.26	0.43	0.29	0.50	-0.17	-0.41	-0.37	-0.48	-0.02*	0.11	0.24	0.05*	-0.09*
CEC (cmolc/kg soil)	-0.31	-0.68	-0.52	-0.27	-0.82	0.31	0.72	0.65	0.80	-0.02*	-0.10	0.11*	0.20	-0.44
ECEC (cmolc/kg soil)	-0.16	-0.29	0.00	0.17	-0.20	0.13	0.20	0.21	0.18	-0.07*	0.02*	0.22*	0.23	-0.29
Exchangeable Na (%)	-0.06	-0.04*	-0.10	-0.25	-0.08	0.00	0.11	0.07	0.06	0.05*	-0.03*	0.71	0.06*	0.15*
Cation Na (meq/kg soil)	-0.13	-0.17	-0.08	-0.16	-0.16	0.03*	0.20	0.15	0.14	0.03*	-0.04*	0.77	0.18	0.04*
Cation K (meq/kg soil)	-0.01*	-0.02*	0.10	0.28	0.09	0.05*	-0.09	-0.01*	-0.12	-0.07*	0.06*	0.40	-0.01*	-0.03*
Cation Ca (meq/kg soil)	-0.07	-0.09	0.19	0.27	0.08	0.05*	-0.06*	-0.01*	-0.09	-0.10	0.10	-0.05*	0.18	-0.26
Cation Mg (meq/kg soil)	-0.15	-0.22	0.03*	0.09*	-0.12	0.16	0.10	0.13	0.12	-0.06*	-0.01*	0.13*	0.23	-0.20
S (total cations) (cmolc/kg soil)	0.09	0.33	0.46	0.35	0.60	-0.19	-0.46	-0.37	-0.65	-0.05*	0.11	0.28*	0.00	0.10*
Exchangeable Mg (%)	-0.12	-0.11	0.05*	-0.02*	-0.03*	0.16	0.00	0.03*	0.04*	0.00	-0.04*	-0.07*	0.10	-0.06*
% CBD Fe	-0.14	-0.56	-0.54	-0.46	-0.80	0.15	0.66	0.54	0.85	0.02*	-0.12	-0.30	0.11	-0.22
Coarse Sand %	1.00	0.53	-0.05	-0.20	0.31	-0.47	-0.25	-0.27	-0.27	0.09	-0.18	-0.22*	-0.16	0.53
Medium Sand %		1.00	0.39	-0.01*	0.77	-0.58	-0.70	-0.70	-0.69	0.01*	-0.02*	0.14*	-0.20	0.60
Fine Sand %			1.00	0.45	0.75	-0.35	-0.59	-0.71	-0.62	-0.01*	0.35	0.62	-0.21	0.26
Very Fine Sand %				1.00	0.33	0.42	-0.25	0.04*	-0.42	-0.37	0.39	-0.09*	0.10*	-0.28
Total Sand %					1.00	-0.48	-0.86	-0.84	-0.93	0.03*	0.14	0.32	-0.27	0.49
Coarse Silt %						1.00	0.49	0.81	0.27	-0.15	0.12	-0.15*	0.18	-0.57
Fine Silt %							1.00	0.89	0.72	0.02*	-0.12	-0.01*	0.24	-0.36
Total Silt %								1.00	0.61	-0.08	-0.14	-0.39	0.26	-0.52
Clay %									1.00	0.02	-0.12	-0.03*	0.21	-0.38

Table A2.5: Correlation matrix: spectrophotometer colour measurements and Redness Index versus soil parameters

Soil property and Colour component	% Organic Carbon	% Extractable Al	pH H ₂ O	CEC (cmolc/kg soil)	ECEC (cmolc/kg soil)	Exchangeable Na (%)	Cation Na (meq/kg soil)	Cation K (meq/kg soil)	Cation Ca (meq/kg soil)	Cation Mg (meq/kg soil)	S (total cations) (cmolc/kg soil)	Exchangeable Mg (%)	% CBD Fe
Redness Index (L*a*b* Dry)	0.19	-0.17	0.12	0.27	0.29	-0.16	-0.06*	0.18	0.28	0.31	0.07	0.20	0.38
L* Dry	-0.25	0.13	-0.09	-0.31	-0.31	0.17	0.02*	-0.18	-0.28	-0.31	-0.05	-0.18	-0.39
a* Dry	-0.45	-0.24	0.19	-0.21	-0.12	0.05*	-0.03*	-0.04*	-0.02*	0.03*	0.04*	0.13	0.09
b* Dry	-0.38	0.04*	-0.03*	-0.26	-0.31	0.15	-0.01*	-0.20	-0.26	-0.23	-0.12	-0.08	-0.14
**Dry Spec. Cont. Hue	0.22	0.31	-0.26	0.04*	-0.12	0.06	0.02*	-0.13	-0.21	-0.23	-0.16	-0.22	-0.20
Dry Spec. Cont. Value	-0.25	0.12	-0.08	-0.30	-0.30	0.17	0.03*	-0.17	-0.27	-0.30	-0.05*	-0.18	-0.39
Dry Spec. Cont. Chroma	-0.47	-0.08	0.08	-0.27	-0.25	0.12	-0.02*	-0.15	-0.17	-0.13	-0.05*	0.01*	-0.05

Table A2.6: Correlation matrix: spectrophotometer colour measurements and Redness Index versus soil parameters

Soil property and Colour component	Coarse Sand %	Medium Sand %	Fine Sand %	Very Fine Sand %	Total Sand %	Coarse Silt %	Fine Silt %	Total Silt %	Clay %	UV (fiSa) - Max/Min	CPSD Index (%)	E Conductivity	Modulus of rupture	Dispersion ratio
Redness Index (L*a*b* Dry)	-0.02*	-0.08	-0.09	-0.17	-0.15	-0.18	0.03*	0.03*	0.22	0.04*	-0.09	-0.33	-0.17	0.21
L* Dry	-0.01*	0.10	0.10	0.17	0.18	0.16	-0.06	-0.06	-0.23	-0.03*	0.09	0.34	0.19	-0.23
a* Dry	0.03*	0.03*	0.04*	0.00	0.08	-0.08	-0.17	-0.16	-0.01*	0.03*	0.02*	0.17*	0.05*	-0.12*
b* Dry	-0.03*	0.01*	0.08	0.08	0.09	0.12	-0.08	-0.10	-0.07	0.01*	0.06*	0.32	0.17	-0.30
Dry Spec. Cont. Hue	-0.06	0.00	0.04*	0.08	0.00	0.19	0.10	0.07	-0.05	-0.02*	0.02*	0.08*	0.06*	-0.08*
Dry Spec. Cont. Value	-0.01*	0.09	0.10	0.16	0.18	0.16	-0.07	-0.06	-0.23	-0.03*	0.09	0.34	0.19	-0.24
Dry Spec. Cont. Chroma	0.00	0.03*	0.07	0.04*	0.11	0.01*	-0.16	-0.15	-0.06	0.01*	0.05*	0.32	0.12	-0.22

Appendix 3 - Supplementary data from Chapter 4

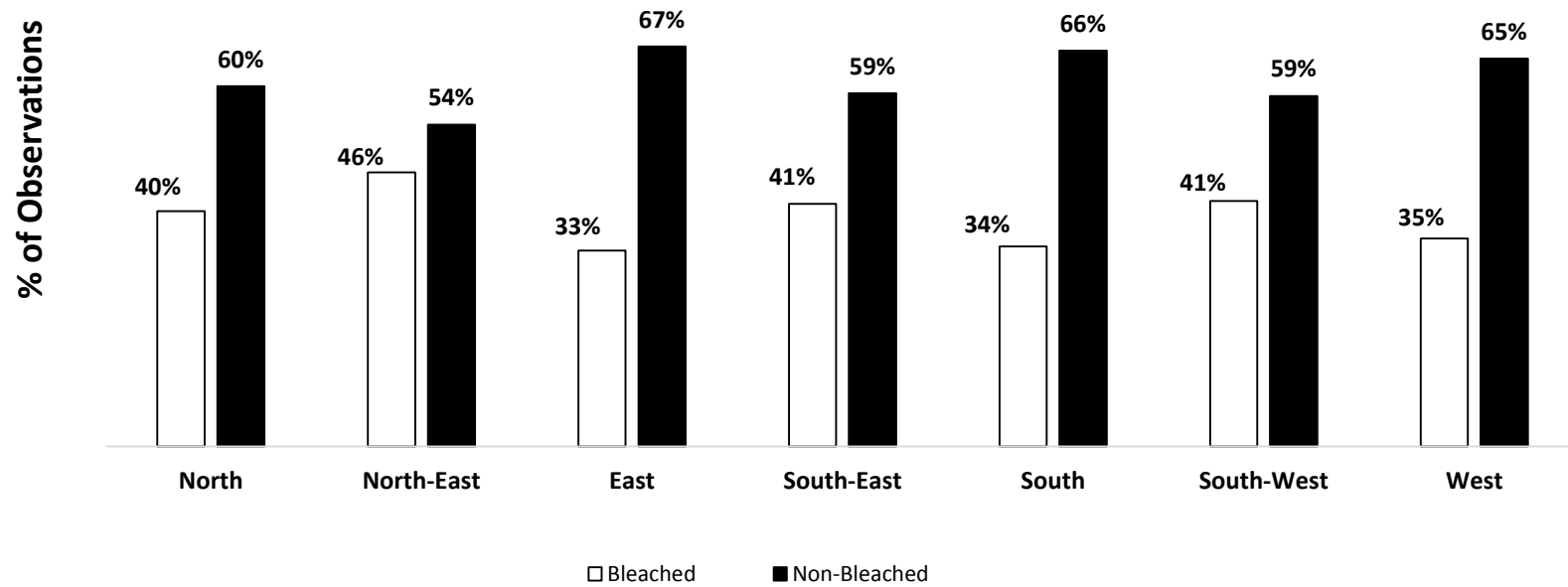


Figure A3.1: Occurrence of topsoil bleaching on different slope aspects (p -value = 0.63)

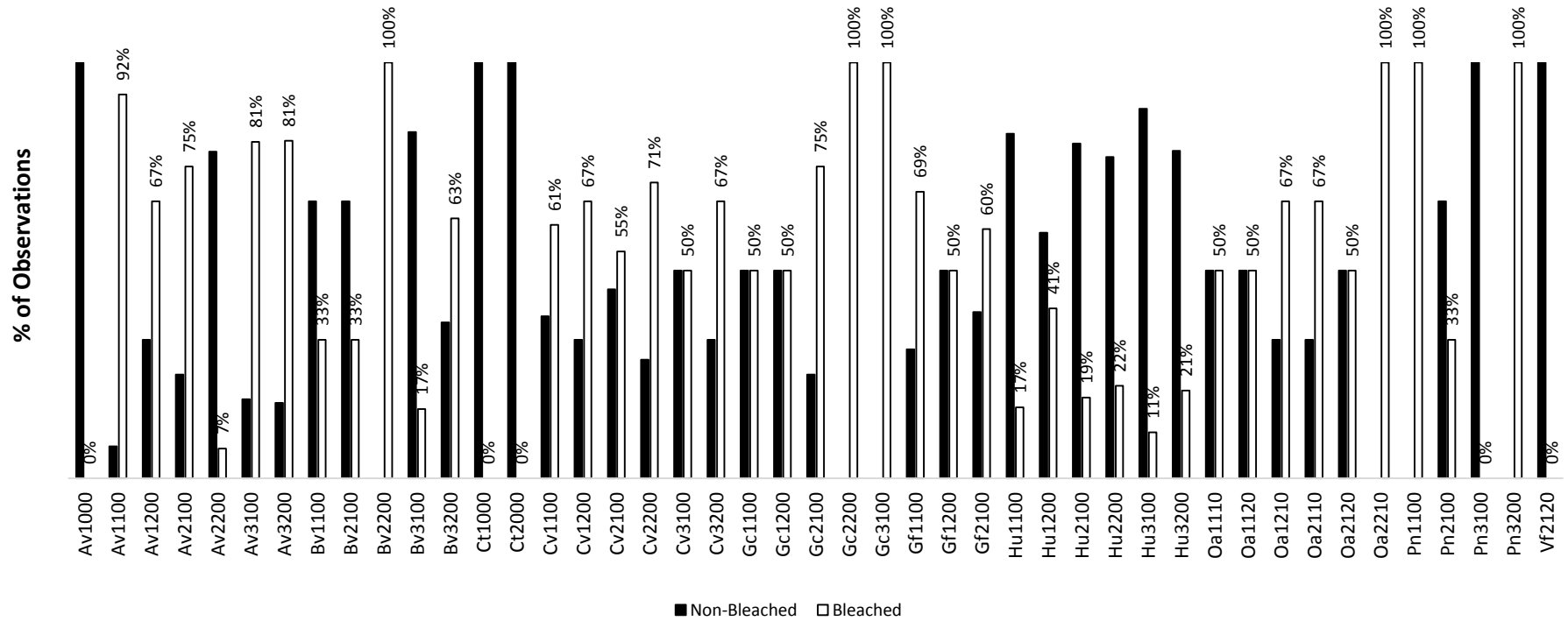


Figure A3.2: The occurrence of bleached and non-bleached topsoils on a soil family level.

Appendix 4 – Land Type Memoirs (methods and materials description)

(Reference: Land Type Survey Staff. 1984. Land types of the map 2522 Bray, 2622 Morokweng, 2524 Mafiking, 2624 Vryburg. Mem. agric. nat. Resour. S.Afr No. 1. Department of Agriculture. Pretoria.)

Introduction

PLANNING THE SURVEY

The land type survey programme commenced in 1972 with the perspective that a sound understanding of the natural agricultural resources of South Africa was required. Essential to the attainment of this objective was a systematically compiled inventory of the natural factors that determine agricultural potential, namely climate, terrain form and soil type. The purpose of the survey was to map and document the natural resources climate, terrain form and soil type. The immediate aims of the survey were:

- the delineation of areas, known as land types, at 1:250 000 scale such that each land type displays a marked degree of uniformity with regard to terrain form, soil pattern and climate,
- the definition of each land type in terms of terrain, soil and climate parameters, and
- an in-depth analysis of a number of soil profiles, termed modal profiles, selected to represent the range of soils encountered during the survey.

With this information it would be possible to define and, with reasonable accuracy, estimate the areas of the main climate – soil – slope classes that occur in each demarcated area. Yield potential and production technique data could be coupled to these classes in information storage-retrieval systems. Climate, terrain form and soil data stored in terms of these classes, or derived from them, could be used as inputs to crop production and other models. The potential benefits for agriculture would be many. For example,

- agricultural advisers would be assisted in providing farmers with reliable information relevant to their specific resource situations,

- it would be possible to determine, on a country-wide basis, where a particular crop could be grown and what it could yield in any particular area,
- for purposes of regional planning, the importance to agriculture of an area could be evaluated in terms of what it could produce, and
- research priorities would be indicated by an inability to predict satisfactorily potential yields and associated production techniques for these classes of land, especially those, which cover large areas of high agricultural potential.

Further agricultural applications have been set out elsewhere (MacVicar, Scotney, Skinner, Niehaus & Laubser, 1974). The survey will add considerably to our knowledge of the natural resources and promote a better understanding of the geomorphic and pedologic development of the landscapes of South Africa. This it will do by presenting simultaneously some of the important causes and effects of genetic processes.

The land type maps are prepared to be superimposed as semi-transparent overprints over 1:250 000 scale topo-cadastral maps, or as complete, printed paper maps. The maps will also be prepared in digital formats suitable for computer map products. Land type and modal soil profile data will be contained in memoirs such as this. Each memoir will deal with one or more land type maps.

HOW TO USE THIS MEMOIR AND ITS ACCOMPANYING MAPS

To find:

1. The land type number. Consult SECTION E: MAPS - Land type map.
2. Soil and terrain data (including a terrain form sketch) for a given land type. Consult the individual land type numbers in SECTION B: SOIL AND TERRAIN INVENTORIES - Index.
3. The significance of land type numbers. Consult SECTION A: INTRODUCTION AND METHODS - Legend to land type maps.
4. The area of a land type on one map. Consult the relevant map.
5. The total area of a land type. Consult the soil and terrain inventory in SECTION B: SOIL AND TERRAIN INVENTORIES - Index.
6. The land type climate zone number. Consult SECTION E: MAPS - Land type climate zone map or SECTION D: CLIMATE ZONE INVENTORIES – Index.
7. Climate data for a given land type climate zone. Consult SECTION D: CLIMATE ZONE INVENTORIES – Climate zone inventories for land types.

8. The numbers of modal profiles in the area covered by the land type map. Consult SECTION E: MAPS - Land type map or SECTION C: MODAL PROFILES - Index.
9. Data on a modal profile. Consult SECTION C: MODAL PROFILES – Profile descriptions and soil analyses.
10. The meaning of headings in the soil analyses tables. Consult SECTION A: INTRODUCTION AND METHODS – Physical, Chemical and Mineralogical Methods.
11. The meaning of headings in the climate zone inventory tables. Consult SECTION A: INTRODUCTION AND METHODS – Climate.

Field Methods

SUMMARY OF FIELD METHODS

The survey of the area covered by a 1:250 000 map was carried out in a stepwise fashion on each of its component 1:50 000 quarter degree sheets. First, existing information and maps, including satellite imagery, relevant to the terrain, soils and climate of the area were collected and studied. Areas called *terrain types*, each displaying a marked uniformity of terrain form, were delineated. Then the soils in each terrain type were identified and areas known as *pedosystems*, each with uniform terrain and soil pattern, were delineated. Representative or modal profiles were described and sampled for in-depth laboratory investigation while additional soil series identification samples were collected and analyses. A separate map showing the distribution of *climate zones* was then drawn. This was superimposed upon the pedosystem map to arrive at a map of *land types*; each displaying marked uniformity of terrain, soil pattern and climate. On completion of these steps the land type boundaries and the climate zone boundaries were digitised from the 1:50 000 maps to create the 1:250 000 maps. Finally, an inventory of each land type was compiled in terms of terrain, soil and climate parameters.

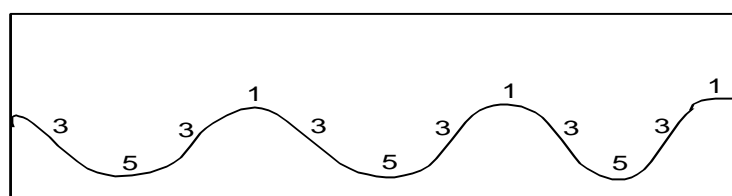
IDENTIFICATION OF TERRAIN TYPES

A terrain unit is any part of the land surface with homogeneous form and slope. Terrain can be thought of as being made up of all or some of the following kinds of terrain units: crest, scarp, midslope, footslope and valley bottom or flood plain. A terrain type (adapted after Kruger, 1973; Hammond, 1964; King 1953) in this context denotes an area of land over which there is a marked uniformity of surface form and which, at the same time, can be shown easily on a map at a scale of 1:250 000. Land shown on a map as belonging in a terrain type may cover only a single terrain unit (e.g. a flood plain), it may cover a single crest-valley bottom sequence (e.g. an escarpment) or it may cover a large number of crest to valley bottom sequences that repeat themselves three-dimensionally (e.g. a large area of rolling hills).

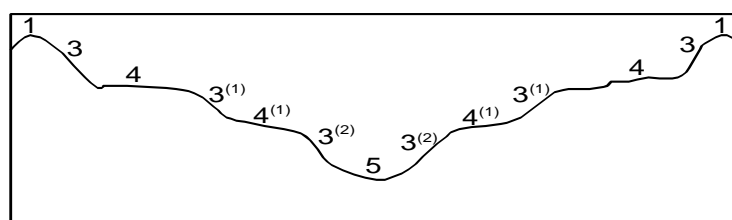
Although the terrain type has genetic implications, morphology and not genesis is the basis of its delineation and description.

In the following diagrams (Figure 1), 1 represents a crest, 2 a scarp, 3 a midslope, 4 a footslope and 5 a valley bottom. 3⁽¹⁾ indicates a second phase midslope and 3⁽²⁾ a third phase midslope. Whether a terrain unit is a footslope or a midslope depends on its position (a midslope lies immediately below a crest or scarp) and, to an extent, upon the steepness of the slope. In contrast with a midslope, a scarp is steeper than 100% (45°) and usually steeper than about 70°.

The maps used in the terrain, soil and climate surveys were 1:50 000 and 1:250 000 topocadastral maps obtainable through the Chief Directorate of Surveys and Mapping. The 1:50 000 maps show contours at 20 m intervals, and the 1:250 000 maps show contours at 50 m intervals.



Single-phase terrain type



Multi-phase terrain type

Figure 1. Schematic diagrams of single and multi-phase terrain form.

The terrain type boundaries were drawn in the office and then field-checked. The criteria for delineation were the pattern and density of the drainage system, relief and the slope, slope profile and extent of each of the terrain units. The terrain inventory was made after the land type boundaries were finalized.

IDENTIFICATION OF PEDOSYSTEMS

A pedosystem (after Verster, 1973) denotes land over which terrain form and soil pattern each display a marked degree of uniformity. Soils do not occur randomly in a landscape, but follow a pattern determined by factors such as geology and topographic position, many of which in turn have either played a part in shaping the landscape or are inherent features of the landscape (e.g. a valley bottom). This inter-relationship between soils and landform is good reason for relating soils to the landscape positions in which they occur; the terrain type provides a suitable framework. In addition, terrain types are convenient compartments of land whereby the soils of a large area can be systematically surveyed, inventorised and presented. The soil composition of a terrain type was described by detailing which soil series of the Binominal System (MacVicar, de Villiers, Loxton, Verster, Lambrechts, Merryweather, le Roux, van Rooyen, and Harmse, 1977) occur on each terrain unit (e.g. the midslope) and by giving an estimate of the area of each series on a given terrain unit.

Each terrain type was traversed systematically, normally by motor vehicle, paying attention to genetic principles such as topomorphism and the effects of geology, in an effort to identify as many as possible of the soils present. By auguring, by using exposures such as road cuttings and occasional soil pits, the soils occupying the terrain units (crest to valley bottom) were identified and their positions marked on the 1:50 000 maps. Where necessary, soil samples were taken for the purpose of series identification. Occasionally access to an area was impossible. In such cases an indication is given of what soils are thought likely to occur.

If the soil pattern (crest to valley bottom) was found to be roughly the same throughout, the terrain type boundary became a pedosystem boundary. Where the soil pattern changed from one part of the terrain type to another, boundaries were drawn within the terrain type to separate these different patterns (two or more) and hence pedosystems.

At this stage modal profiles sites were identified, pits dug and the profiles described and sampled. Analytical facilities required that these profiles, chosen to represent the range of soils encountered during the survey, be limited in number.

IDENTIFICATION OF CLIMATE ZONES

The climate map required was one which would show the distribution of climate zones within each of which all agriculturally important climate parameters would display either a narrow range of variation or a marked regularity in pattern of variation. It soon became clear that a map of this sort at 1:250 000 scale could not be prepared within a reasonable period of time

using climate measurements alone: meteorological stations were too widely scattered and in most cases recorded too few climate parameters.

The procedure used (MacVicar, 1973) therefore placed great reliance on natural vegetation, soils, crop performance, altitude and topography as indicators of climate boundaries. Beginning at a point, for example in the middle of a plain and moving in a given direction, the investigator, aided by the knowledge gained from prior terrain form and soil surveys of the area, placed the climate boundaries. The surveyor having established a boundary, would continue working outwards from the original starting point until all the climate zones fulfilling the requirements set out above had been determined. Where all or several of the indicators (climate measurements, natural vegetation, altitude, topography, soils, and crop performance) pointed to a climate boundary, for example along the edge of an escarpment, the task was easy and accurate, meaningful boundaries could be drawn. Over large plains where climate changes gradually, the task was more difficult and the positioning of boundaries was attended by a degree of uncertainty. In the latter instances as much reliance as possible was placed on the evidence of climate measurements, while soil and vegetation characteristics, and crop performance, helped considerably. In placing the boundaries, the investigators were assisted to a greater or lesser extent in different parts of the country by other knowledgeable persons.

Some climate zones cover no more than a terrain unit (e.g. a plateau, a flood plain), some a single crest-valley bottom sequence, while many cover a large number of crest to valley bottom sequences that repeat themselves three-dimensionally (e.g. a large undulating plain). Tablelands may display greater uniformity of climate than rolling hills where climate differences may occur from crest to valley bottom, N-slope to S-slope and so on. While the map does not demarcate these differences, it does provide a means of accurately referring to them and, if necessary, demarcating them on larger scale maps. For example, in a climate zone characterized by rolling hills, all the valley bottoms will have marked uniformity of climate, so also all the crests, likewise the N-slopes and so on. Points on a horizontal line along the slope of an escarpment climate zone will also display marked uniformity of climate. In this sense it is perhaps permissible to regard many of the climate zones as macroclimate zones within which mesoclimate differences occur.

A number of agriculturally important climate parameters were chosen to define the climate of each zone. In a large number of zones data were not available for all the chosen parameters and in some cases no data at all were available. Spatial interpolation techniques were used to estimate climate parameters over the whole region using multiple linear regression techniques. In most cases regular estimates were made at a 300 m grid interval. The climate tables were constructed by averaging these grid estimates within a climate zone. The chief

source of data (both measured and interpolated) has been the database of the Agrometeorology Division of the ARC-Institute for Soil, Climate and Water that incorporates data from other organizations such as the Weather Bureau.

Improved definitions of the climate of these zones will be possible in future as the number of meteorological stations is increased. The present shortage of data does mean, however, that it is difficult to state the relationships between certain zones in either qualitative or quantitative terms.

THE LAND TYPE MAP

A land type denotes an area that can be shown at 1:250 000 scale and that displays a marked degree of uniformity with respect to terrain form, soil pattern and climate. One land type differs from another in terms of one or more of terrain form, soil pattern and climate. Other land types may separate different occurrences of the same land type from one another. The land type map was compiled by superimposing the climate map on the pedosystem map. The land type inventory was then compiled using data collected during the terrain, soil and climate survey phases.

A climate zone may cover a portion of a pedosystem, it may have the same boundary as a pedosystem or it may cover two or more pedosystems. In order to improve the usefulness of land type maps, solid black, broken red and solid red lines are used to show land type boundaries. *Solid black* indicates a pedosystem boundary; that is, the climate on either side is the same but terrain form and/or soil pattern are different on either side. *Broken red* indicates a climate boundary only; the pedosystem is the same on either side. *Solid red* is a climate and a pedosystem boundary; here the possibilities are: climate, terrain form and soil pattern are different on either side; climate and terrain form are different on either side; climate and soil pattern are different on either side. Frequently, therefore, the boundary of a single land type is shown as part solid black, part broken red and part solid red. These different lines make it possible to draw a climate zone map (by omitting solid black lines) or a pedosystem map (by omitting broken red lines) of an area.

On each map a list is given of the modal profiles that are located on it; the positions of these profiles are also shown. The co-ordinates, description and analytical data for each profile are contained in the memoir that deals with the land type inventories for the particular 1:250 000 map. On each map is a list of the numbers of the land types that occur on that map. In addition, the area (ha) of each separate occurrence of every land type is given.

LEGEND TO THE LAND TYPE MAPS

Broad soil patterns (*vide infra*) were chosen at the start of the survey for the purpose of constructing a common legend for the land type maps. These broad soil patterns and their associated colours have a restricted function, namely to

- improve the readability of the maps and
- to give the reader an indication of the soils of the area.

It was also considered convenient to number the land types according to these broad soil patterns. Each land type was allocated a number by placing it in the broad soil pattern (defined in the paragraphs that follow) that accommodated it and then giving it the next available number in the soil pattern. Thus land type number Ea39 was given to the thirty-ninth land type that qualified for inclusion on broad soil pattern (or map unit) Ea. Often, land belonging to the same land type occurs as islands separated by other land types. Each such separate occurrence is identified using the system Ea 39a, Ea39b etc. A single occurrence of a land type may occur on two map sheets; the same system of postscripts is used to indicate the two portions of the land type. Since these postscripts indicate different occurrences of the same land type, they are not part of the land type number. There follows a list of the soil patterns and a description of the soils to which each refers. Technical terms are explained in the book “Soil Classification: A Binomial System for South Africa” (MacVicar *et.al.*, 1977).

*Red-yellow apedal, freely drained soils (map units **Aa – Ai**)*

Map units **Aa – Ai** refer to yellow and red soils without water tables and belonging to one or more of the following soil forms: Inanda, Kranskop, Magwa, Hutton, Griffin, Clovelly. The map units refer to land that does not qualify as a plinthic catena and in which one or more of the above soil forms occupy at least 40% of the area. In **Aa**, humic soil forms occupy at least 40% of the area. In **Ab** (red, dystrophic and/or mesotrophic), yellow soils occupy less than 10% of the area while dystrophic and/or mesotrophic soils occupy a larger area than high base status red-yellow apedal soils; the same rule, with appropriate adaptation, applies for units **Ad** (yellow, dystrophic and/or mesotrophic), **Ae** (red, high base status, > 300 mm deep, no dunes), **Af** (red, high base status, > 300 mm, with dunes), **Ag** (red, high base status, < 300 mm deep) and **Ai** (yellow, high base status). **Ac** (red and yellow dystrophic and/or mesotrophic) indicates land with red and yellow soils each of which covers more than 10% of the area while dystrophic and/or mesotrophic soils occupy a larger area than high base status red and yellow apedal soils. The same rule, with appropriate adaptation, applies for unit **Ah** (red and yellow, high

base status). Dunes in unit **Af** refer to a regular rather than a single or occasional occurrence of dunes.

*Plinthic catena: upland duplex and marginalitic soils rare (map units **Ba – Bd**)*

A very large area of the South African interior is occupied by a catena that in its perfect form is represented by (in order from highest to lowest in the upland landscape) Hutton, Bainsvlei, Avalon and Longlands forms. The valley bottom is occupied by one or other gley soil (e.g. Rensburg, Willowbrook, Katspruit, Champagne forms). In addition to these, Glencoe, Wasbank, Westleigh, Kroonstad, Pinedene and Tambankulu (rare) forms, and Klipfontein and (occasionally) Hillside soils series, are found. Soils with hard plinthite are particularly common over sandstones in the moist climate zones in the eastern parts of the country. Depending on the extent to which water tables have been operative over a landscape, Longlands and Avalon and related grey and yellow soils may predominate, even to the exclusion of red soils. Where water tables have not extended far beyond the valley bottoms, red soils may predominate with plinthic soils restricted to narrow strips of land around valley bottoms or pans. However, plinthic soils must cover more than 10% of the area for it to qualify for inclusion in units **Ba - Bd** and **Ca**. Upland duplex and marginalitic soils are absent or occupy less than 10% of the area in units **Ba – Bd** but occupy more than 10% of the area in unit **Ca**. Upland marginalitic soils include one or more of Arcadia, Bonheim, Tambankulu, Mayo and Milkwood forms; upland duplex soils include one or more of Estcourt, Sterkspruit, Swartland, Valsrivier and Kroonstad forms. Unit **Ba** indicates land in which red and/or yellow apedal soils (Hutton, Bainsvlei, Avalon, Glencoe and Pinedene forms) that are dystrophic and/or mesotrophic predominate over red and/or yellow apedal soils that are eutrophic, and in which red soils (mainly Hutton and Bainsvlei) occupy more than a third of the area. The same rule, with appropriate adaptation, applies to units **Bb** (dystrophic and/or mesotrophic, red soils not widespread), **Bc** (eutrophic, red soils widespread) and **Bd** (eutrophic, red soils not widespread).

*Plinthic catena: upland duplex and/or marginalitic soils common (map unit **Ca**)*

Unit **Ca** indicates land that qualifies as a plinthic catena (see discussion on map units **Ba – Bd**) but which has, in upland positions, marginalitic and/or duplex soils (see discussion on map units **Ba – Bd**) that together cover more than 10% of the total area.

*Duplex soils dominant (map units **Da – Dc**)*

Units **Da – Dc** accommodate land where duplex soils are dominant. Upland soils that display duplex character include Estcourt, Sterkspruit, Swartland, Valsrivier and Kroonstad forms. After subtracting exposed rock, stones or boulders, more than half of the remaining land must consist of duplex soils. **Da** refers to land where duplex soils with red B horizons comprise more

than half of the area covered by duplex soils. **Db** refers to land where duplex soils with non-red B horizons comprise more than half of the area covered by duplex soils. **Dc** indicates land that qualifies for inclusion in D but, in addition to the duplex soils, more than 10% of the land type is made up of soil forms that have one or more of the following diagnostic horizons: vertic, melanic, red structured.

*One or more of: vertic, melanic, red structured diagnostic horizons (map unit **Ea**)*

This unit indicates land with high base status, dark coloured and/or red soils, usually clayey, associated with basic parent materials. A land type, more than half of which is covered by soil forms with vertic, melanic and red structured diagnostic horizons, qualifies for inclusion in unit **Ea** provided it does not qualify for inclusion in units A, B or C. Land types in which these soils cover less than half of the area may also qualify for inclusion (i) where duplex soils occur in the non-rock land but where unit **Ea** soils cover a larger area than the duplex soils, or (ii) where exposed rock covers more than half the land type.

*Glenrosa and/or Mispah forms (other soils may occur) (map units **Fa – Fc**)*

This group of map units is intended to accommodate pedologically young landscapes that are not predominantly rock and nor predominantly alluvial or aeolian and in which the dominant soil-forming processes have been rock weathering, the formation of orthic topsoil horizons and, commonly, clay illuviation, giving rise typically to lithocutanic horizons. The soil forms that epitomise these processes are Glenrosa and Mispah. However, exposed rock and soils belonging in almost any of the other 39 soil forms may be found in these land types, provided these other soils do not qualify the land for inclusion in another map unit. Shallow and deep soils of the Oakleaf form (usually on upland sites) developed by rock weathering (e.g. gneiss, aeolianite etc.) are accommodated here. **Fa** refers to land in which lime in the soil is not encountered regularly in any part of the landscape. **Fb** indicates land where lime occurs regularly (there need not be much of it) in one or more valley bottom soils. **Fc** refers to land where lime occurs regularly (there need not be much of it and it need not occur in every soil present) in upland and valley bottom soils. Lime has been used as an indicator of the extent to which youthful landscapes have been leached. Occasionally landscapes are encountered without lime but with accumulations of soluble salts in the soil; these have been included in **Fb** or **Fc** as the case may be.

*Soils with a diagnostic ferrihumic horizon (map units **Ga, Gb**)*

The intention here is to highlight those parts of South Africa in which podzols occur. After subtracting exposed rock, the land type qualifies for inclusion here if more than 10% of the remaining area is covered by soils of Lamotte and/or Houwhoek forms, provided the area

covered by these soils exceeds the area covered by soils that would qualify the land type for inclusion in map units Aa – Ai, Ba – Bd, Ca, Da – Dc, Ea, Ib or Ic. Therefore land may qualify for inclusion in units **Ga** and **Gb** even though the area covered by Lamotte and Houwhoek soils is less than the area covered by soils characteristic of one or more of map units Fa – Fc, Ha and Hb, and Ia. That is, podzolic land takes precedence over other forms of pedologically youthful land, except land that is largely composed of exposed rock. The symbols **Ga** and **Gb** are used to indicate dominance of Lamotte and Houwhoek forms respectively.

*Grey regic sands (map units **Ha, Hb**)*

These units accommodate areas in which deep grey sands of Fernwood form are a prominent feature. Constantia, Shepstone and Vilafontes forms are included here. **Ha** indicates land types in which soils of these forms occupy more than 80% of the area. **Hb** indicates land types with less than 80% and more than 20% of the area covered by these soils; soils of units Fa–Fc can be dominant. With the exception of Fa – Fc as described above, the land does not qualify for inclusion in other map units.

*Miscellaneous land classes (map units **Ia – Ic**)*

Ia refers to land types with a soil pattern difficult to accommodate elsewhere, at least 60% of which comprises pedologically youthful, deep (more than 1 000 mm to underlying rock) unconsolidated deposits. Common soil forms are Dundee and Oakleaf. **Ib** indicates land types with exposed rock (exposed country rock, stones or boulders) covering 60 – 80% of the area. **Ic** refers to land types with exposed rock (exposed country rock, stones or boulders) covering more than 80% of the area. The rocky portions of **Ib** and **Ic** may be underlain by soil which would have qualified the unit for inclusion in another broad soil pattern were it not for the surface rockiness.

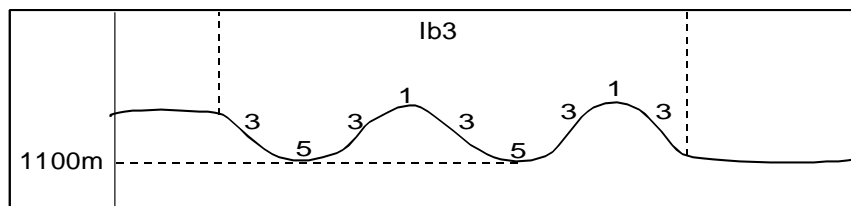
Land Type Inventory

As indicated earlier the land type inventory is made up of three parts, namely terrain form, soil and geology, and climate.

TERRAIN

General

- (a) A profile sketch is given of the terrain type indicating the land type by its number (in this example lb3) and giving, approximately, the altitude (m) of the lowest point in the land



type.

Percentage level land is estimated (with the aid of a slope wedge) in terms of four classes:

- A - more than 80% of the area has slopes less than 8%
- B - 50 - 80% of the area has slopes less than 8%
- C - 20 - 50% of the area has slopes less than 8%
- D - less than 20% of the area has slopes less than 8%

- (b) Local relief is an estimate of the difference (m) over the land type between the highest (unit 1) and lowest (unit 5) points in the landscape. The estimate was made by considering a number (depending on the size of the land type) of $7\frac{1}{2} \times 7\frac{1}{2}$ minute sample areas. It is expressed in terms of six classes as follows:

Class 1	0 – 30 m
Class 2	30 – 90 m
Class 3	90 – 150 m
Class 4	150 – 300 m
Class 5	300 – 900 m
Class 6	> 900 m

- (c) Using the criteria given in (b) and (c) above, a symbol (e.g. A2) indicating the nature of the terrain type is given in the inventory of each land type.

Terrain units

The terrain type is described in terms of the terrain units and phases of terrain units present. Each terrain unit (whether phase 1, 2 or 3 etc.) is defined according to its:

- (a) range in percentage slope (using a slope wedge);
- (b) range in length (m);
- (c) shape: concave (X), convex (Y), straight (Z);

(d) area (ha).

GEOLOGY

A brief description is given of the rock type and the geological formation present in the land type in their order of dominance. Information is generally derived from the published 1:250 000 scale geology map (Geological Survey, 1984) and is used in conjunction with the published 1:1 million scale geology map of South Africa (Geological Survey, 1984).

SOIL

Estimates are given of the areas (ha)

(a) not available for agriculture; that is, the area occupied by towns, roads, dams and pans where these are recorded on the current edition maps.

The occupancy of each terrain unit is estimated in terms of percentages of the following units (in a survey of this nature it cannot be claimed that all the soils in each land type have been found and identified):

- (a) Soil series present. In addition, for each series, estimates are given of depth range (depth of the surface and the upper subsoil materials generally including the A, E and B horizons), clay content ranges of topsoils and upper subsoils and the most common texture class or classes of the indicated horizon. Plus and minus signs indicate 25 – 35% clay and 15 – 25% clay respectively. The symbols (including those for soil form and soil series, and the depth-limiting material) used are those given in the Binomial System (MacVicar, *et.al.*, 1977) or explained in this text.
- (b) Soil-rock complex. The rock component described in the soil rock complex occurs as small rocky areas intimately associated with soil. Dolerite boulders in a soil matrix are an example of a soil rock complex. The rock is not as large areas of rock devoid of soil. In addition, estimates of the percentages of rock and of each soil series in the complex are given.
- (c) Solid rock. Exposed country rock with little or no soil.
- (d) River and streambeds.
- (e) Pans. These are depressions, often wet, from which there is no surface drainage.
- (f) Erosion.
- (g) Swamps.
- (h) Shifting dunes.

- (i) Coarse deposits. These include alluvial and colluvial deposits of stones and boulders. Where soils were identified in (e) – (i), they are listed.

The mechanical limitations associated with each class of land (see previous paragraph) are described in terms of the classes set out below. The limitations are due to stoniness and/or shallowness.

MB0 – no mechanical limitations

MB1 – many stones, but ploughable

MB2 – large stones and boulders, unploughable

MB3 – very shallow soils on rock

MB4 – lack of soil

CLIMATE

A climate zone contains one or more land types. Each climate zone has a number. The climate zones on a land type map are listed in the index of the memoir that deals with that map. After each number a letter (S, W or H) appears which is not part of the climate zone number; it simply indicates seasonal distribution of rainfall; S = summer rainfall (with a distinct period of relatively low rainfall in winter), W = winter rainfall (with a distinct period of relatively low rainfall in summer), H = all year rainfall (with no distinct period of relatively low rainfall). Each climate zone is defined in terms of as many of the weather elements (e.g. rainfall, maximum temperature) as available data at the time of publication of this memoir permitted. Several factors limit the accuracy of the data reflected for each climate zone. These include the total number of weather stations that can be associated with a climate zone (many climate zones are described with few or no weather stations); the number of weather elements (e.g. rainfall, maximum temperature) recorded at the weather stations; and the length of reliable record for these elements. Finally the accuracy of values for weather elements reflected in inventories is also dependant on the accuracy and relevance of any spatial interpolation methodology that has been applied. There is no record of the positions in the landscape of weather stations so that relationships between climate and landscape positions within a climate zone can be made.

Rainfall

- (a) Mean annual total from the grid cell with the highest mean annual rainfall (abbrev. Rh).
- (b) Mean annual total from the grid cell with the lowest mean annual rainfall (abbrev. RI).

- (b) Mean annual total from the mean annual totals of all interpolated grid points (abbrev. R).
- (c) Mean of mean monthly totals (12 months) from the mean monthly values for all interpolated grid points, normalised to according to the mean annual total rainfall grid (abbrev. Rm).
- (d) Probable monthly rainfall: The rainfall threshold can be expected to be exceeded for each month
 - for 60% of years (12 months)(abbrev. P60Rm) (Grid data not currently available.)
 - for 80% of years (12 months)(abbrev. P80Rm) (Grid data not currently available.)

Evaporation (Penman)

- (a) Total monthly evaporation for each month (mm) is derived from the Linacre (1992) simplifications of the Penman (1948) formula for potential evaporation (12 months) (abbrev. Penman). An annual value for evaporation (PET) sums the mean daily evaporation values over 12 months. The mean altitude of the climate zone and the latitude of the midpoint were used in the estimation of PET. Since wind data was not available, a daily average wind speed of 3 m/s was used. Readers are cautioned that the Penman (PET) evaporation values are in the region of 60-80% of typical A-Pan evaporation values.

Temperature

- (a) Mean daily maximum temperature for each month from all interpolated grid points (abbrev. Tx).
- (b) Mean daily minimum temperature for each month from all interpolated grid points (abbrev. Tn).
- (c) Monthly mean temperature: the mean of each month of the daily $\frac{(\max + \min)}{2}$ from

All interpolated grid points (abbrev. Tm).

- (d) Mean monthly maximum temperature: the mean of monthly maxima for a given month (abbrev. Txh).
- (e) Mean monthly minimum temperature: the mean of monthly minima for a given month (abbrev. Tnl).
- (f) Heat units (expressed in degree days) above 10°C. Heat units refer to the difference between the average temperature, $\frac{(\max + \min)}{2}$, and a base temperature (here 10°C),

2

Summed over chosen periods (here October – March and April – September), on a daily basis.

- (i) Mean total for October to March, on a daily basis, from the interpolated grid points with the highest total of units for the period (abbrev. HEomH).

- (ii) Mean total for October to March, on a daily basis, from the interpolated grid points with the lowest total of units for the period (abbrev. HEomL).
- (iii) Mean of the mean totals, on a daily basis, from all interpolated grid points for October to March (abbrev. HEom).
- (iv) Mean total from April to September, on a daily basis, from the interpolated grid points with the highest total of units for the period (abbrev. HEasH).
- (v) Mean total from April to September, on a daily basis, from the interpolated grid points with the lowest total of units for the period (abbrev. HEasL).
- (vi) Mean of the mean totals, on a daily basis, from all interpolated grid points for April to September (abbrev. HEas).

Frost (minimum Stevenson screen temperature $\leq 0^{\circ}\text{C}$)

- (a) Average first date (from all stations) (abbrev. FDm)
- (b) Average last date (from all stations) (abbrev. LDm).
- (c) Average duration, in days, of the frost period (from all stations) (abbrev. FP).
- (d) Earliest frost date (abbrev. FDe).
- (e) Latest frost date (abbrev. FDI).
- (f) Percentage of years in which frost occurs (from all stations) (abbrev. PF).
- (g) Mean number of frost days (from all stations) (abbrev. MFd).

Grid data for first and last frost dates is not currently available.

Methods of Soil Description and Analysis

PROFILE DESCRIPTION METHODS

A comprehensive soil profile description was prepared including information on the profile number, the soil classification class and geographic location. Site information, together with a detailed description of each horizon are included. The descriptive procedure followed that outlined by Verster (1973) and subsequently adapted by Idema, Dohse and van der Walt (1986) and by the Land Type Survey Staff (1991). These descriptive methods were based on those of the Soil Survey Manual (Soil Survey Staff, 1951). Abbreviations used in the descriptions are those contained in the Binomial System (MacVicar *et.al.*, 1977). The Munsell system (Munsell Color Company, 1971) was used to determine soil colour. Classes used for stoniness and erosion are as follows:

Stoniness

Stones larger than 250 mm in diameter and rock outcrops are grouped together since both have an important bearing on soil use. On the one hand they interfere with the use of agricultural machinery and on the other they dilute the soil mass.

Class 0	No stones or bedrock or too few stones to interfere with tillage.
Class 1	Sufficient stones or bedrock to interfere with tillage but not to make intertilled crops impracticable.
Class 2	Sufficient stones or bedrock to make tillage of intertilled crops impracticable, but soil can be worked for hay crops or improved pasture if other soil characteristics are favourable.
Class 3	Use of all but very light machinery and hand tools impracticable, forestry and grazing possible.
Class 4	Use of all machinery impracticable, forestry and grazing possible.
Class 5	More than 90% of the land surface covered by stones or exposed bedrock.

Erosion

Kind:

Sheet erosion.	Uniform removal of topsoil from an area without the development of conspicuous water channels.
Rill erosion.	Removal of soil through the cutting of numerous small but conspicuous water channels.
Gully erosion.	Removal of soil giving rise to deep channels or gullies.
Wind erosion.	Removal of topsoil by wind.

Class:

Class 1	None apparent or slight.
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|---------|---|
| Class 2 | Moderate loss of topsoil and/or some slight dissection by run-off channels or gullies. |
| Class 3 | Severe loss of topsoil and/or marked dissection by run-off channels or gullies. |
| Class 4 | Total loss of topsoil and exposure of sub-soil and/or deep intricate dissection by gullies. |

SAMPLE PREPARATION

The sample preparation procedure underwent several changes and improvements, the biggest change being that from sample crushing and sieving at ARC-ISCW (1972-1979) to crushing and sieving by hand under the pedologist's supervision (1979 – present). The two procedures followed were, respectively:

- Samples collected in the field were air-dried and sent to ARC-ISCW in plastic bags contained within canvas sample bags. Samples were dried further if necessary, and a quantity of soil sufficient for the laboratory analysis was machine crushed using a porcelain mortar and steel pestle (Nasco-Aspelin grinder), and sieved through a 0,065 inch (1,68 mm) mesh sieve.
- Samples were air-dried and a quantity of soil sufficient for laboratory analysis was crushed by hand using a porcelain mortar and pestle and sieved through a 2 mm sieve. The mass of material >2 mm was noted. The crushed and remaining uncrushed soil was sent to ARC-ISCW for analysis and storage.

PHYSICAL METHODS

Particle size distribution

Details of the method are described by Day (1965). Organic matter was removed from an air-dried soil sample (10 g) by oxidation with 30% H₂O₂ (10 cm³). Carbonates were destroyed by adding sufficient 2 mol/l HCl. The soil suspension was flocculated with 10% CaCl₂ (10 cm³), suction filtered and soluble salts leached from the soil. Dispersion was accomplished by means of stirring (7 000 rpm for 10 min) after adding dispersing agent (10 cm³). Up to and

including sample C5376, 0.1 mol/l NaOH was used. On certain kinds of soil materials dispersion was inadequate and clay percentages were low; therefore a sodium hexametaphosphate dispersing agent (Calgon) was used from sample C5377 onwards. This was prepared by dissolving 35.7 g Na-hexametaphosphate and 7.9 g Na_2CO_2 in water, making up to 1 litre and adjusting to a pH of 8.5 with a saturated solution of Na_2CO_3 . The hexametaphosphate dispersant was used in preference to a 1 mol/l NaOH solution which tests showed gave better dispersion with some sesquioxidic soils but caused flocculation with many other samples. As a result of a comparative study some 600 earlier analyses were repeated or adjusted.

For most of the earlier samples, five particle size fractions were determined. Clay ($<2 \mu\text{m}$ settling diameter) and silt (2-20 μm) were determined by sedimentation and pipette sampling. The sand fractions, fine (0.02–0.2 mm), medium (0.2–0.5 mm) and coarse (0.5–2 mm) were determined by dry sieving. As the survey progressed, a seven fraction determination was introduced. The size classes are: clay ($<2 \mu\text{m}$), fine silt (2-20 μm), coarse silt (0.02-0.05 mm), very fine sand (0.05-0.1 mm), fine sand (0.1-0.25 mm), medium sand (0.25-0.5 mm) and coarse sand (0.5-2.0 mm). Particles larger than 2 mm were excluded, but due to the use of a different sieve, particles larger than 1.68 mm were excluded on earlier samples. Results are expressed as a percentage of the mass of oven-dried soil. All size fractions were determined individually and none was estimated by difference. Unless large amounts of OM or carbonates were present in the original sample, totals were required to lie between 94% and 103%.

Since complete dispersion of particles remained difficult in certain sesquioxidic soils, water percentage (m/m) at – 1 500 kPa (see water retentivity) multiplied by a factor of 2.5 (Soil Survey Staff, 1975), was used to obtain additional estimates of clay percentage for certain potentially problematic horizons. The horizons concerned are red and yellow-brown apedal and red structured horizons with base saturation values of less than 50%.

Dorbank samples (duripans) were treated differently from other soils for the purpose of particle size distribution analysis. Air-dry fragments (mass 20 – 50 g) were treated with citrate-bicarbonate-dithionite (CBD) (see MINERALOGICAL METHODS, Extractable Fe and Al, for concentrations and quantities used) on a hot water bath at 70°C until most iron oxide coatings were removed (fragment surfaces grey in colour but usually retaining most of their hardness). The CBD solution was then largely removed from the fragments by immersing them in de-ionised water several times and decanting the supernatant liquid. The fragments were then immersed in 2 mol/l NaOH at room temperature for three days after which they were easily crushed with a glass rod. The NaOH was decanted and the soil washed repeatedly using de-ionised water and decantation until most of the NaOH was removed. The samples were again

washed with distilled water on a Buchner funnel to remove most of the soluble salts. After drying, the samples were passed through a 2 mm sieve and analyzed by the normal method.

Air to water permeability ratio

The air to water permeability ratio of a soil is a measure of the effect of water on the pore size distribution of the soil and hence of its tendency to swell and/or disperse. The intrinsic permeability of a porous medium is a function of the size, shape and geometry of pores and is independent of fluid properties such as density and viscosity. The permeability of a stable porous medium to water is in theory equal to that measured using air as a fluid. Swelling and dispersion effects cause the air permeability of a soil sample to be higher than the subsequently measured water permeability. A completely stable porous material has a ratio of one while 20 roughly indicates the threshold of instability in soils. Highly dispersed soils may have air to water permeability ratios of several hundred to infinity.

Reeve (1965) describes details of the method used. Sufficient soil which had been crushed to pass a 2 mm mesh sieve was packed into a 50 mm diameter plastic permeameter to form a column about 40 mm high after tamping. The air permeability of the soil column was determined. The water permeability of the same column was measured after de-ionised water had flowed through the sample for 4 hours. A single air to water permeability ratio was measured for each sample. According to Reeve, individual determinations can be expected to be within 10% of the mean 75% of the time and within about 20% of the mean 80% of the time.

Modulus of rupture

The modulus of rupture is a concept relating to the breaking strength of beams and one used extensively for predicting the strength of materials. It is used as a measure of cohesion in dried soils. It is increased by all factors that promote close packing and contact between mineral particles, such as fine grinding, dispersion, certain particle size distribution patterns and low organic matter content. The modulus of rupture can be related to surface crusting and clod formation. Crusts having values greater than 80 kPa are likely to impede seedling emergence in the case of sensitive crops.

Details of the method are described by Reeve (1965). Soil which had been crushed to pass a 2 mm mesh sieve was packed into a rectangular frame mould, saturated for at least 6 hours with de-ionised water and dried at about 45°C in a forced draught oven. The resulting soil briquette was supported at either end and a steadily increasing force was applied to a knife-edge across the center of the briquette until failure occurred. The modulus of rupture was

calculated from the force required to break the briquette and the dimensions of the briquette and the knife-edge assembly. Two briquettes were prepared for each sample; the results reported being mean values. Coefficients of variation were found by Reeve to lie between 0.5% and 15% for different soil samples.

Water retentivity

Traditionally the amount of water held between field capacity (a matric potential of about -10 to -35 kPa) and wilting point (about $-1\ 500$ kPa) has been accepted as representing plant available water. Estimates obtained in this way are approximate since other factors such as hydraulic conductivity, soil morphology, plant root characteristics and climate should be taken into account. Plant available water is best estimated by measuring water content in the field and relating it to field capacity and permanent wilting of crops. The method described by Richards (1965) was applied to disturbed samples. Single determinations at each of four potentials (-33 , -80 , -500 and -1500 kPa) were made using appropriate ceramic plate extractors. Samples were contained in rubber rings 10 mm high and 50 mm in diameter. The samples were saturated with tap water for at least 16 hours and at least 3 days were allowed for equilibration under pressure.

CHEMICAL METHODS

Total exchangeable acidity and exchangeable aluminium

The procedure outlined by McLean (1965) with modifications set out below, was used. A 10 g soil sample was shaken with 70 cm³ mol/litre KCl solution in a 100 cm³ slopy neck plastic bottle on a reciprocating shaker at a minimum of 180 oscillations per minute for 1 hour. The suspension was filtered through Whatman No. 2V filter paper into a 500 cm³ Erlenmeyer flask and washed with an additional 30 cm³ 1 mol/litre KCl solution. Total exchangeable acidity was determined on the KCl extract by titration with 0.1 mol/litre NaOH. Excess NaF was added to the titrated solution and the OH⁻ ions so released were titrated with 0.1 mol/litre HCl to determine exchangeable aluminium. In both titrations phenolphthalein was used as indicator. Exchangeable hydrogen was obtained by difference. All results were expressed as me/100 g soil or cmol (+)/kg soil.

Exchangeable and soluble cations, cation exchange capacity, titratable acidity and electrical conductivity

The procedure is that of USDA (1972; reported in Soil Classification Working Group (1991)). Ammonium acetate (NH₄OAc), 1M, pH7: Mix 68.0 cm³ ammonium hydroxide (NH₄OH),

specific gravity 0.90, with 57.5 cm³ 99.5% acetic acid (CH₃COOH) for each dm³ of solution required. Cool, dilute to volume with water and adjust to pH7 with acetic acid or ammonium hydroxide. Optionally prepare by dissolving 77.0 g NH₄OAc in 1 dm³ water. Adjust with acetic acid or ammonium hydroxide.

Centrifuge method: Add 10 g <2 mm air dry soil to a weighed 100 cm³ centrifuge tube. Add 50 cm³ 1M NH₄OAc. Shake for 1 hour and allow to stand overnight. Centrifuge at 2 000 – 5 000 rpm until supernatant is clear. Decant clear supernatant into a 100 cm³ volumetric flask. Add a further 50 cm³ 1M NH₄OAc, shake for 30 min., centrifuge and decant into the same volumetric flask. Fill the volumetric flask to the mark with 1M NH₄OAc, filter and retain the filtrate for the determination of NH₄OAc extractable cations (solution A). Add 50 cm³ 0.1 M NH₄OAc to the centrifuge tube, shake for 30 min. and centrifuge. Decant clear supernatant into a bottle and retain for determination of the concentration of the ammonium in the occluded solution (Solution B). Determine the total mass of the centrifuge tube, soil and occluded NH₄OAc (Mass X₂). Add 50 cm³ 1M KCl, shake for 30 min., centrifuge and decant clear supernatant into a 200 cm³ volumetric flask. Repeat with a further 50 cm³ 1M KCl and make up to the mark with 1 M KCl (Solution C).

Direct steam distillation of adsorbed ammonia: Add 10 cm³ boric acid indicator solution to a 100 cm³ Erlenmeyer flask marked to indicate a volume of 50 cm³. Place the flask under the exit of a condenser of the steam distillation apparatus. In separate distillations, pipette 5 cm³ of ammonium acetate (Solution B) or 10 cm³ of the KCl extract (Solution C) into the distillation flasks. Increase the volume to about 20 cm³ with de-ionised water. Add 1 teaspoon (2.5 cm³) heavy MgO through a dry funnel into the bulb of the flask. Connect the distillation flask without delay to the steam generator and distil to a volume of about 50 cm³ in the flask containing the boric acid indicator. Stop steam distillation by opening the stopcock on the steam by-pass tube and then remove the distillation flask. Rinse the exit tube of the condenser. Determine NH₄⁺ by titrating with 0.05 mol dm³ sulphuric acid. The colour change at the end point is from green to a permanent faint pink.

Direct determination of extractable and exchangeable bases: Sodium and potassium in the NH₄OAc leachate are determined with a flame photometer or by atomic absorption spectrophotometry. Calcium and magnesium in the NH₄OAc leachate are determined by atomic absorption spectrophotometry in a 1 000 mg dm³ La solution as releasing agent and /or a 1 000 mg dm³ Cs solution as ionizing buffer (the latter is more applicable with a N₂O acetylene flame). Express the concentration of the exchangeable cations in cmol(+) kg⁻¹ soil.

Uncorrected (extractable) bases: If a soil does not contain soluble salts, the extractable bases are presumed to be equal to exchangeable bases. They are however reported as extractable bases.

Corrected (exchangeable) bases: If a soil contains soluble salts (i.e. resistance of the soil paste <460 ohms measured in a standard USDA soil cup, or specific conductivity of saturation extract >200 mS m^{-1}), determine the concentration ((mmol(+) dm^3)) of soluble bases in a saturation extract. Multiply base concentration in saturation percentage and divide by 1 000, to convert to cmol(+) kg^{-1} soil. Subtract this quantity from the concentration of extractable bases. This procedure is not valid for calcium and magnesium in soils containing free carbonates and /or gypsum.

Soluble cations were determined separately in soils containing significant quantities of soluble salts. These were subtracted from the NH_4OAc -extractable cations to obtain the exchangeable cations.

For soils with an electrical resistance of less than 460 ohms, the exchangeable cations were estimated by subtracting the cations in the saturation extract (see below) from the total extractable cations. In soils containing lime or gypsum or those with a very high salt content, not all the water-soluble salts were dissolved in the saturation extract. In these cases the figure for total exchangeable cations is higher than the CEC.

Cations in the saturation extract were determined as follows (USSL Staff, 1954). A 250 g air-dry soil sample is placed in a suitable container and moistened with de-ionised water while mixing with a spatula. Consolidate the mixture from time to time by tapping on the work bench. Test for the properties of a saturated paste and add more de-ionised water if necessary. Allow to stand for at least an hour and test whether it still has saturation properties. If left overnight cover the container. Special care should be taken to ensure that water does not collect and that the paste does not dry out too much. Add more de-ionised water if required. If too much water is added, repeat procedure. Note the total volume of water added.

Properties of a saturated paste: In a saturated paste all the pores are filled with water. It has the following characteristics: The surface is shiny; the paste flows slightly when the container is tilted; free water does not collect when a small trench is drawn on the surface and it does not cling to the spatula (with the exception of clayey soil).

Conductivity of the saturation extract was measured and expressed in mS/m. Determination of Na, K, Ca and Mg is the same as that for the extractable cations.

pH measurements

Two pH measurements were made, one on a 1:2.5 soil to water suspension and one on a suspension prepared by adding 25 cm³ 0.01 mol/litre CaCl₂ solution to 10 g soil. In both instances, suspensions were stirred intermittently for 15 min and allowed to stand for at least 1 hour. The electrodes were positioned in the supernatant liquid.

Electrical resistance of the saturated paste

A saturated paste was prepared as described by the USSL Staff (1954). The soil paste was allowed to stand for 4 hours and the resistance determined in a US Bureau of Soils cup using a Thornley and Yntema Type BC12 resistance bridge. Results were given in ohms.

Organic carbon

The Walkley-Black method as described by Allison (1965) was used with the following modifications. The soil was ground to pass a 44 mesh (approx. 0.355 mm) sieve and masses of 0.5 g, 1 g or 2 g were used, depending on the amount of carbon present. Instead of 20 cm³, 15 cm³ conc. H₂SO₄ was used. An amount of 196 g (NH₄)₂ Fe(SO₄)₂·6H₂O plus 5 cm³ conc. H₂SO₄ was made up to 1 litre to replace the ferrous sulphate o-phenanthroline monohydrate solution used to back-titrate the unreacted K₂Cr₂O₇ (initially 0.5 mol/l).

Phosphorus status

Phosphorus was extracted using a slightly modified version of the ISFEI method described by Hunter (1975). Instead of a 1:10 soil to solution ratio on a volume basis, a 1:10 ratio on a mass basis was used. Ten minutes of stirring was replaced by 30 min of shaking at 180 oscillations per minute. Phosphorus was determined in the extract by means of the molybdenum blue method using an auto-analyser. The P status is expressed as mg/kg soil.

Phosphorus sorption

Phosphorus sorption (adapted after McGee, 1972) of P from solution was measured in order to identify soil materials likely to fix large quantities of fertilizer P. Air-dried soil (2 g, later 8 g) was shaken with 50 cm³ (later 200 cm³) of a 10 mg/litre P solution (prepared from KH₂PO₄ to which was added 4.46 g CaCl₂ and 10 cm³ HCHO per 20 litres of solution) in an end-over-end shaker at 40 rpm for 24 hours. The soil suspensions were filtered through Whatman No. 42 filter paper and P determined in the clear filtrate by the molybdenum blue method using an

auto analyser. The sorption reaction is temperature-sensitive and was therefore carried out under controlled temperature ($20^{\circ}\text{C} \pm 2^{\circ}$) conditions.

Sorption was expressed as a percentage of the P added (250 mg/kg soil). In the case of soils giving sorption percentages higher than 98%, the procedure was repeated using a 100 mg/litre P solution instead of a 10 mg/litre P solution. This gave a better discrimination among soils with high P-sorption characteristics. The results provide an empirical index of the P-sorption ability of the soil and are not necessarily directly related to fertilizer requirements. This procedure using the lower and where necessary the higher P concentration was followed for samples from 25 land type maps (Land Type Survey Staff, 1984). Samples from all other areas were treated only with 100 mg/litre P solution and centrifuged.

Micronutrients (Cu, Mn, Zn, Co, B)

For the determination of micronutrients in soil samples, the multiple soil extractant used was di-ammonium EDTA (Beyers and Coetzer, 1971). Soil (10 g) was shaken up with 100 cm³ of 0.02 mol/litre (NH₄)₂ EDTA at pH 4.6 for 60 min, centrifuged, filtered, and 80 cm³ of the filtrate evaporated to dryness in a silica dish and ashed in a furnace at 500°C. The ash was moistened with distilled water and a drop of HNO₃, where after it was again ashed at 500°C for 15 min. After cooling, the residue was taken up in 2.5 cm³ of 1:1 constant boiling point HCl solution containing Li (2%) and Sr (4%).

Up until the analysis of sample C3340 a direct reading spectrometer was used to determine Cu, Zn, Mn, Co and B in the prepared solutions. From sample C3341 to C4496 solutions obtained in the same way were analysed for all these elements, with the exception of B, on an atomic absorption spectrometer. Dilution of the extracts was however necessary because of high acid concentrations as well as the need to adjust the readings to the range of the atomic absorption apparatus. Boron was extracted with the warm water reflux extraction procedure and the B content of the extract determined calorimetrically according to the curcumin method described by Jackson (1958).

In order to increase throughput, precision and accuracy, and thereby reduce costs, a modified procedure for determining Cu, Zn, Co and Mn was introduced from sample C4497 onwards. The (NH₄)₂ EDTA solution concentration and time of extraction remained unchanged but the soil to extractant ratio was adjusted and the ashing procedure omitted. In the case of Cu, Zn and Co determinations, 5 g soil was shaken up with 15 cm³ of (NH₄)₂ EDTA for 60 min in a plastic bottle. For Mn, the original soil to solution ratio of 1:10 was maintained. It should be

noted that for soils containing free lime the buffer action of EDTA is inadequate to prevent an increase in pH of the extract. After shaking, the soil suspension was centrifuged in the same plastic bottle and thereafter filtered through 90 mm diameter Whatman No. 40 filter paper. Concentrations of elements in the extracts were determined directly with an atomic absorption spectrometer. Only in the case of soils with high Mn contents was it necessary to dilute the extract 10-fold.

Before any change in procedure was accepted, duplicate analyses were carried out using the original and modified methods. Results were statistically analysed and no significant differences were found. Micronutrient content is expressed as mg/kg of soil.

MINERALOGICAL METHODS

Pretreatment

The methods described by Jackson (1956) were modified to facilitate the handling of a large number of samples. All samples received the same pretreatment. Sufficient soil to yield between 6 and 12 g clay was weighed into a plastic 500 cm³ centrifuge bottle and treated with 200 cm³ 1 mol/litre NaOAc (buffered at pH 5) in a water bath at 70°C with intermittent stirring to dissolve carbonates. After centrifuging, the NaOAc was poured off and discarded. To remove as much Ca as possible, the sample was shaken up with an additional 200 cm³ 1 mol/litre NaOAc, centrifuged, and the supernatant discarded. Organic matter was removed by adding 50 cm³ 30% H₂O₂ and stirring. After the initial vigorous reaction had subsided, the removal was brought to completion on a water bath. The procedure was repeated with 20 cm³ H₂O₂ for most soils, but with 50 cm³ for soils rich in organic matter. To the peroxide treated samples 300 cm³ 1 mol/litre NaCl was added, shaken by hand, centrifuged and the supernatant decanted.

Extractable Fe and Al

Deferration was carried out by adding 200 cm³ Na-citrate/bicarbonate buffer (pH 8.5) solution (0.3 mol/litre Na-citrate and 1.0 mol/litre NaHCO₃), shaking the sample into suspension and adding about 10 g Na-dithionite and allowing it to react with intermittent stirring on a water bath at 70°C. After the colour became completely grey (about 30 min), the suspension was centrifuged and the citrate-dithionite extract was poured off into pre-weighed plastic bottles. A further washing with 200 cm³ Na-citrate/bicarbonate solution was done and after centrifuging, the supernatant was added to the plastic bottles. Iron, and in certain samples also aluminium,

was determined in the extract by atomic absorption and the results recorded as per cent (*m/m*) Fe and Al on a soil (< 2 mm) basis.

Particle size separation and Mg-saturation

The centrifuged sample was washed with 300 cm³ 1 mol/litre NaCl and thereafter with 300 cm³ de-ionised water. The sample was then wet-sieved (50 µm sieve), collecting the less than 50 µm fraction in 3.8 litre glass bottles and discarding the sand fraction. The suspension was flocculated by adding 50 – 100 g NaCl and the supernatant siphoned off. The less than 50 µm fraction was transferred to plastic centrifuge bottles for separation of the clay (< 2 µm) and silt (for convenience 2 – 50 µm fractions as described by Jackson (1956)). The 2 – 50 µm fraction was saturated with Mg (using 0.5 mol/litre Mg(OAc)₂ and MgCl₂) and dried in an oven at 70°C. The clay fraction was flocculated by adding 100 cm³ 0.5 mol/litre Mg(OAc), and the supernatant siphoned off. The clay fraction was transferred to 250 cm³ glass centrifuge bottles and centrifuge-washed twice with 100 cm³ 0,5 mol/litre MgCl₂. The samples were centrifuge-washed with de-ionised water until Cl⁻ free (AgNO₃ tested) and freeze-dried.

X-ray diffraction analysis

X-ray diffraction (XRD) analyses were carried out on a Philips unit with PW 1010/25 generator, PW 1050/25 goniometer and AMR 3 – 202 graphite monochromator, using CoK α radiation, a 1.0° divergence slit and 0.1° receiving slit, and a proportional counter. Standard experimental conditions were 45 kV, 40 mA, a scanning speed of 2° 2θ/min, paper speed 25.4 mm per min, and variable rate meter settings (usually R4 or R8).

Parallel or “preferred” orientated deferrated clay specimens were examined by XRD after preparation on unglazed ceramic tiles (method used was similar to that described by Rich, 1969). The 2 – 50 µm fraction was initially examined in the Mg-saturated form on glass slides (first 1 000 samples) and thereafter in randomly orientated form by pressing samples in aluminum holders against a filter paper surface (Fitzpatrick, 1978). Ferricrete and calcrete samples were finely ground in an agate mortar and examined by XRD in a randomly orientated form as above.

To differentiate between various layer silicates, Mg-saturated samples solvated with glycerol, and K-saturated samples heated at 110°C and 550°C were examined (Jackson, 1956). In cases where confirmation of certain minerals was required, the chemical method described by Alexiades and Jackson (1966) together with thermal (differential thermal analysis and thermogravimetric analysis) and infrared analysis was used. From sample C5797, Mg-

saturated air dried samples, as well as Mg-saturated samples solvated with ethylene glycol and K-saturated air dried samples were included in the procedure.

Relative intensities or peak heights of X-ray diffraction peaks were used as estimates of the approximate amounts of minerals present in the sample and are expressed as very strong (peak height 75 – 100 in relative units), strong (50 – 75), medium (25 – 50), weak (5 – 25) and very weak (0 – 5). It should be noted that quantitative estimations of different minerals in the separates by comparison of intensities of X-ray diffraction peaks is not reliable because individual minerals differ in mass absorption coefficient, orientation of grains, crystal perfection and chemical composition. Therefore, at most, even when the interpretation of the diffractograms is made with caution, the peak height values can serve only as a semi-quantitative indicator of the amounts of minerals present.

Modifications

From sample C5797, the following procedures were adopted. The < 2 μm and 2 – 50 μm fractions were collected in 250 cm^3 bottles after sedimentation phase of particle size analysis (see PHYSICAL METHODS, Particle size distribution). The clay was saturated with Mg (using 1 mol/litre MgCl_2) and repeatedly shaken up with de-ionized water and centrifuged until chloride-free (AgNO_3 tested) and freeze-dried. The 2 – 50 μm fraction was dried overnight at 70°C.

X-ray diffraction analysis was carried out on both size fractions using the method described above. Extractable Fe and Al were determined separately on 1 g samples as described above.

Mineral symbols used by the ARC-Institute for Soil, Climate and Water

Aa	-	Aragonite
An	-	Anatase
Ap	-	Allophane
Bd	-	Beidellite
Bm	-	Boehmite
By	-	Bayerite
Ch	-	Chlorite
Ch(2:1)-	-	Chloritized 2:1 minerals
Cp	-	Pedogenic chlorite
Ct	-	Calcite

Dt	-	Dolomite
Fh	-	Ferrihydrite
Fs	-	Feldspar
Gb	-	Gibbsite
Go	-	Goethite
Gy	-	Gypsum
Hb	-	Hornblende
HI	-	Halite
Hm	-	Hematite
Ht	-	Halloysite
Ig	-	Imogolite
Il	-	Illite
Im	-	Ilmenite
Is	-	Interstratified clay minerals
Jr	-	Jarosite
Kt	-	Kaolinite
Lp	-	Lepidocrocite
Ma	-	Magnetite
Mh	-	Maghemite
Mi	-	Mica
Ms	-	Magnesite
Mt	-	Montmorillonite
My	-	Metahalloysite
Nt	-	Nontronite
Pl	-	Palygorskite
Ps	-	Pseudorutile
Py	-	Pyrophyllite
Qz	-	Quartz
Rt	-	Rutile
Sp	-	Sepiolite
St	-	Smectite

Tc	-	Talc
Un	-	Unidentified crystalline material
Vm	-	Vermiculite
Zi	-	Zircon

XRD peak height intensities

1	-	very weak	(0 – 5 relative units)
2	-	weak	(5 – 25 relative units)
3	-	medium	(25 – 50 relative units)
4	-	strong	(50 – 75 relative units)
5	-	very strong	(75 – 100 relative units)

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