SOIL CHEMICAL AND PHYSICAL PROPERTIES AND THEIR INFLUENCE ON THE PLANT SPECIES RICHNESS OF ARID SOUTH-WEST AFRICA

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DECLARATION

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

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ABSTRACT

Understanding the drivers and mechanisms of changes in plant richness is a basis for making scientifically sound ecological predictions and land use decisions. Of the numerous factors affecting plant richness, soil has a particularly large influence on the composition and structure of terrestrial flora. Infiltrability is one of the most important factors determining soil moisture, and therefore is of particular interest in semi-arid ecosystems, where water is one of the most limiting resources. Other soil properties, such as clay + silt content, electrical conductivity (EC) and pH may also influence plants. Heterogeneity of these properties creates niches with specific conditions, which in turn affects spatial distribution of plants. An understanding of the relationships between plant richness and soil properties is, however, incomplete. The present study has two main foci. Firstly, relationships between plant richness and soil infiltrability, clay + silt, EC and pH (H_2O) were investigated, and secondly, due to the strong influence of infiltrability on plant richness, further investigations were undertaken to improve the understanding of the role of particle size fractions, EC of the soil solution and exchangeable sodium percentage (ESP) on infiltrability. This study only concentrated on the surface 2 cm thick soil layer (known as pedoderm).

The study was conducted at a large-scale and was based at 31 study observatories located along a transect stretching from the western seaboard of South Africa to Namibia, and encompassing four biomes, namely: Succulent Karoo, Nama Karoo, Savanna and Woodland. Plant species data for each plot were obtained from the BIOTA[1] South database and categorized into 5 life form categories using Raunkiaer's (1934) classification system: phanerophytes (trees), chamaephytes (shrubs), hemicryptophytes (grasses), therophytes (annuals) and geophytes. A total of 313 soil samples were analysed for infiltrability, particle size distribution, EC and pH. In order to investigate the effect of soil texture on infiltrability, small intervals of water-dispersible soil fractions were determined. A laser technique was used for particle size determination, which allowed for the determination of smaller particle size fractions than is possible with conventional laboratory techniques. To investigate the effect of dispersion, flocculation, EC and ESP infiltrability was measured using four different infiltration solutions: namely, distilled water; gypsum solution; 1:5 soil suspension in gypsum solution, and 1:5 soil suspension in water. The infiltrability of samples with different particle

[1] Abbreviation for: "Biodiversity Monitoring Transect Analysis in Africa".

size distributions and ESP values were compared.

A relational envelope approach was used for the data interpretation. The derived envelopes showed ranges along soil property gradients, where plant richness was potentially maximal or predictably restricted. A segmented quantile regression was used to delineate boundary lines representing 0.95 and 0.1 quantiles. These boundary lines circumscribed envelopes in which 85 % of observations occurred.

The results of this study revealed that soil infiltrability, water-dispersible clay + silt, EC and pH appeared to influence richness of life forms. Patterns for potentially maximal richness along soil properties gradients differed between life forms. Phanerophytes and hemicryptophytes had potentially maximal richness at high infiltrability, low clay + silt and low EC. By contrast, richness of chamaephytes and geophytes was potentially maximal at low infiltrability values, high clay + silt and high EC. Richness of therophytes showed a hump-shaped response to infiltrability and clay + silt with potentially maximal richness at intermediate values. Richness of all life forms was restricted at pH > 9. The observed relationships may be attributed to the effect of an individual soil factor, as well as to the complex effect of a number of soil factors, as they tend to be correlated with one another. This correlation makes it difficult to distinguish which soil factor plays the controlling role. In addition, numerous other factors such as the interaction between species, plant architecture or climate (which were not investigated in the present study) may affect plant richness. Therefore, causality cannot be demonstrated from the relational envelopes, but they do provide an enhanced understanding of ecological processes.

Dispersion of soil particles resulting in crust formation on the soil surface was found to be a dominant mechanism reducing infiltrability. Water-dispersible clay + silt showed better correlation with infiltrability than total clay + silt. In terms of soil fractions, soil clay, fine silt, coarse silt, very fine sand and fine sand fractions (< 120 μm) played a plasmic role in soil crusts, i.e., filling in pores and restricting infiltrability. At a content of these fractions in soils above ~ 5 %, infiltrability was predictably restricted, while below ~ 5 % it was potentially maximal. High variability in infiltrability of samples with a plasmic fraction (i.e., < 120 μm) content below ~ 5 % indicated that some other factors may play a primary role in these samples. The < 70 μm fraction appeared to play the most significant role at restricting infiltrability, as at < 2 % content of this fraction infiltrability showed a trend of being higher

than at > 2 % content.

The fraction in the 120-200 μm range showed no clear relationship with infiltrability, in that it could play either a plasmic or skeletal role, depending on its ratio to the < 120 μm fraction and to the > 200 μm fraction. Fine, medium and coarse sand fractions (> 200 μm) were found to play a skeletal role i.e., forming pores that promoted infiltrability. At levels above 50 % of these fractions, infiltrability was potentially maximal. This potentially maximal infiltrability was also explained by the concomitant decrease in plasmic fraction content with an increase of the skeletal fraction.

Soil texture was found to play a primary role in crust formation with EC and ESP being of secondary importance. In the silty loam group, with clay + silt content above 70 %, infiltrability was restricted to the point where EC and ESP did not play a significant role. In the sand and loamy sand groups with a clay + silt content below 18 %, however, EC and ESP played a significant role. In the sand group, soils with high ESP had lower infiltrability than soils with low ESP. An application of gypsum resulted in an increase in infiltrability. This increase probably related to an increase in EC of the soil solution and a concentration of exchangeable Ca^{+2} which negated the dispersing effect of high ESP. The effect of gypsum was apparent only in a treatment where crust formation took place (i.e., in treatment with soil suspension), which suggests that the ameliorating effect of gypsum is likely to take place only in soils which have dispersed or are in the process of dispersing in the field.

The present study enhanced the understanding of the relationships between richness of life forms of plants and soil properties, as well as the effect of soil particle size, EC and ESP on soil infiltrability. Improving this understanding is of critical importance for planning the sustainable management of semi-arid ecosystems.

UITTREKSEL

Die dryfkrag en meganismes wat veranderinge in plantverskeidenheid veroorsaak vorm ‘n basis om wetenskaplik korrekte ekologiese voorspellings en landsgebruik besluite te neem. Van die vele faktore wat plantverskeidenheid affekteer, het die grond ‘n besondere groot invloed op die samestelling en struktuur van aardse flora. Infiltreerbaarheid is een van die belangrikste faktore wat grondwaterinhoud bepaal en is dus van besonderse waarde in semi-ariede eko-sisteme, waar water een van die mees beperkende faktore is. Ander grond eienskappe, soos klei- en slik inhoud, elektriese geleiding (EG) en pH kan ook plante beïnvloed. Heterogenesiteit van hierdie eienskappe skep verskillende nis areas met spesifieke toestande, wat die ruimtelike verspreiding van plante beïnvloed. Die verhouding tussen plant verskeidenheid en grond eienskappe word egter nie voldoende verstaan nie. Hierdie studie het twee hoof fokuspunte. Eerstens is die verhouding tussen plantverskeidenheid en grond infiltreerbaarheid, klei- en slik inhoud, EG en pH (H_2O) ondersoek, en tweedens, vanweë die sterk invloed van infiltreerbaarheid op plantverskeidenheid, is verdere ondersoek ingestel om die rol wat deeltjiegrootteverspreiding, EG van die grond oplossing en die uitruilbare natrium persentasie (UNP) in infiltreerbaarheid speel, beter te verstaan.

Die studie was op ‘n groot skaal uitgevoer op 31 persele geleë in ‘n strook wat strek vanaf die Weskus van Suid-Afrika tot in Namibië. Die area sluit vier plantbiome in, naamlik Sukkulente Karoo, Nama Karoo, Savanna en Woudland. Plant spesie data vir elke perseel is verkry van die BIOTA[2] Suid databasis en is in 5 lewensvorm kategorieë ingedeel deur van Raunkiaer (1934) se klassifikasie sisteem gebruik te maak. Die lewensvorme is: phanerofiete (bome), chamaefiete (struike) hemikriptofiete (grasse) therofiete (jaargewasse) en geofiete. ‘n Totaal van 313 grondmonsters is geanaliseer vir infiltreerbaarheid, deeltjiegrootte-verspreiding, EG en pH. Om die effek van grond tekstuur op infiltreerbaarheid te ondersoek, is klein intervalle van water gedispergeerde grondfraksies bepaal. ‘n Laser tegniek is gebruik vir die deeltjiegrootte bepaling, wat dit moontlik maak om kleiner deeltjiegrootte fraksies te bepaal as wat moontlik is met konvensionele laboratorium tegnieke. Om die rol van dispersie, flokkulasie, EG en UNP op infiltreerbaarheid te bepaal, is die effekte van vier verskillende infiltrasie oplossings vergelyk, nl. gedistileerde water, ‘n gips oplossing, ‘n 1:5 grond

[2] Afkorting vir “Biodiversity Monitoring Transect Analysis in Africa”.

oplossing in ‘n gips oplossing en ‘n 1:5 grond oplossing in water. Die infiltreerbaarheid van die monsters met verskillende deeltjiegrootteverspreidings en UNP waardes is vergelyk.

‘n Verhoudings- omhulsel benadering is gebruik om die data mee te interpreteer. Die afgeleide omhulsel het reekse langs grond eienskapgradiënte getoon waar plant verskeidenheid potensieel ‘n maksimum of voorspelbaar beperk sal wees. ‘n Gesegmenteerde kwantiel regressie is gebruik om grenslyne af te beeld wat 0.95 en 0.1 kwantiele verteenwoordig. Hierdie grenslyne het omhulsels afgebaken waarin 85 % van die waarnemings geval het.

Die resultate van hierdie studie het getoon dat grond infiltreerbaarheid, water dispergeerbare klei en slik, EG en pH die verskeidenheid van lewensvorme beïnvloed. Patrone vir potensiële maksimale verskeidenheid langs grond eienskap gradiënte verskil tussen verskillende lewensvorme. Phanerofiete en hemikriptofiete het potensiële maksimale verskeidenheid getoon by hoë infiltreerbaarheid, lae klei en slik inhoud en lae EG. In teenstelling hiermee, is die verskeidenheid van chamaefiete en geofiete potensieel maksimaal by lae infiltreerbaarheid, hoë klei en slik inhoud en hoë EG. Verskeidenheid by therofiete het ‘n boggelagtige respons tot infiltreerbaarheid en klei en slik inhoud getoon, met potensiële maksimale verskeidenheid by intermediêre waardes. Verskeidenheid van alle lewensvorme is beperk by pH > 9. Die waargenome verhoudings kan toegeskryf word aan die effek van ‘n individuele grondeienskap, tesame met die kompleks effek van verskeie grondeienskappe, aangesien die grondfaktore geneig is om met mekaar te korreleer. Hierdie korrelasie maak dit moeilik om te onderskei watter factor die oorheersende rol speel. Tesame hiermee is daar verskeie ander faktore soos die interaksie tussen plant spesies, plant argitektuur en die klimaat (wat nie in hierdie studie ondersoek is nie), wat ook die verskeidenheid van lewensvorme kan beïnvloed. Om hierdie redes kan die oorsaak van plant verskeidenheid nie deur die verhoudings koeverte bepal word nie, maar die koeverte stel ons in staat om die ekologiese prosesse beter te verstaan.

Daar is gevind dat dispersie van gronddeeltjies, wat ‘n kors op die grondoppervlak veroorsaak, ‘n dominante meganisme is wat infiltreerbaarheid laat afneem. Water dispergeerbare slik- en klei-inhoud gee ‘n beter korrelasie met infiltreerbaarheid as totale slik en klei-inhoud. In terme van grond fraksies, speel grond klei, fyn slik, growwe slik, baie fyn sand en fyn sand fraksies (< 120 μm) ‘n plasmiese rol in grond korse deur porieë te vul en

infiltreerbaarheid te beperk. By ‘n totale inhoud van hierdie fraksies in grond van meer as ~ 5 %, is infiltreerbaarheid voorspelbaar beperk, terwyl onder ~ 5 % was die infiltreerbaarheid potensieel maksimaal. Die hoë variasie in infiltreerbaarheid van monsters met ‘n plasmiese fraksie (d.w.s. < 120 µm) inhoud van onder ~ 5 % wys daarop dat ander faktore wel ‘n primêre rol in hierdie monsters kan speel. Dit blyk dat die < 70 µm fraksie die belangrikste rol speel in die beperking van infiltreerbaarheid, met ‘n < 2 % inhoud van hierdie fraksie wat ‘n neiging wys van hoër infiltreerbaarheid as by ‘n > 2 % inhoud.

Die fraksie in die 120-200 µm reeks het geen duidelike verhouding met infiltreerbaarheid getoon nie, deurdat dit beide ‘n plasmiese of ‘n raamwerk rol kan speel, afhangende van die verhouding tot die < 120 µm fraksie en die > 200 µm fraksie. Daar is gevind dat fyn, medium en growwe sand fraksies (> 200 µm) ‘n raamwerk rol speel, deurdat dit porieë vorm wat infiltreerbaarheid bevorder. By vlakke bo 50 % van hierdie fraksies, is infiltreerbaarheid potensieel maksimaal. Hierdie potensiële maksimale infiltreerbaarheid word verduidelik deur die gepaardgaande afname in die plasmiese fraksie inhoud met ‘n toename in die raamwerk fraksie inhoud.

Daar is gevind dat grond tekstuur ‘n primere rol in korsvorming speel met EG en UNP wat van sekondêre belang is. In die slikleem groep, met klei en slik inhoud bo 70 %, was infiltreerbaarheid beperk tot op ‘n punt waar EG en UNP nie ‘n beduidende rol speel nie. In die sand en leemsand groepe met ‘n klei en slik fraksie onder 18 % het die EG en UNP egter ‘n beduidende rol gespeel. In die sandgroep, het gronde met ‘n hoë UNP ‘n laer infiltreerbaarheid gehad as gronde met ‘n lae UNP. Aanwending van gips het ‘n toename in infiltreerbaarheid tot gevolg gehad. Hierdie toename is waarskynlik toe te skryf aan ‘n verhoging in EG van die grond oplossing en konsentrasie van uitruilbare Ca^{+2} wat die dispergerende effek van UNP negeer. Die effek van gips was slegs sigbaar in die behandeling waar korsvorming plaasgevind het (in behandeling met grond oplossing), wat aandui dat die ameliorerende effek van gips waarskynlik slegs sal plaasvind in gronde wat gedispergeer het, of besig is om te dispergeer in die veld.

Na die huidige studie kan die verhoudings tussen verskeidenheid van lewensvorme van plante en grondeienskappe, sowel as die effek van grond deeltjie grootte, EG en UNP op grond infiltreerbaarheid beter verstaan word. Die bevordering van hierdie begrip is van kritiese belang by die beplanning van volhoubare bestuur van semi-ariede eko-sisteme.

This thesis is dedicated to my parents for their constant encouragement and support.

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INTRODUCTION

The study presented in this thesis forms part of the BIOTA southern Africa long-term ecological observation program initiated in 1999 by the German Federal Ministry of Education and Research. BIOTA is an interdisciplinary programme, spanning the natural and social sciences, which aims to increase the understanding of the main drivers causing changes in biodiversity in southern Africa and eastern Namibia (Krug et al., 2006).

This thesis focuses on an investigation of soil properties playing an important role in the composition and structure of terrestrial flora (Huston, 1980; Tilman, 1982). A particular interest was given to infiltrability, as it is one of the most important factors determining soil moisture, and therefore is of primary importance in semi-arid areas, where water is a limiting resource (Cody, 1989; Scholes et al., 1997). It has been reported that moisture availability may significantly affect plant species richness, however, there are some contradictions in the findings to date. This lack of consensus is possibly because soil moisture depends not only on the amount of precipitation received, but also on temperature, runoff and movement of water into a soil profile, or infiltrability; aspects which are often not considered in studies on plant richness. Soil crusting is of relevance for understanding the distribution of plants in arid and semi-arid landscapes, because the crusting process can greatly restrict infiltrability (Shainberg and Letey, 1984) thereby reducing soil moisture and therefore affecting seedling emergence (Eghbal et al., 1996). The crusting process may result in considerable heterogeneity in soil water content at a micro, meso and macro scale, which in turn may affect vegetation structure.

Despite the importance of crust formation and infiltrability, their effects on plant richness are largely undetermined. The role of some soil properties determining infiltrability is also unclear. It is widely recognised that soil electrical conductivity (EC), pH and exchangeable sodium percentage (ESP) significantly affect clay dispersion and crust formation, and in turn soil infiltrability (Agassi et. al., 1981; Levy and Van der Watt, 1988; Le Bissonnais, 2003), however, the modifying effect of texture on the effect of these properties is not well understood. No consensus has also been reached with regards to the role of clay and very fine sand fractions in crust formation. In addition to affecting soil infiltrability, soil texture, EC and pH may also have an effect on plant richness. The role of these properties in semi-arid southern Africa is still, however, unknown.

The present study aims at understanding the relationships between plant richness and soil properties. Quantification of these relationships is likely to yield information that will assist in developing sustainable management practices in semi-arid ecosystems. The research was conducted at a large-scale, and based at 31 study observatories located along a transect stretching from the western seaboard of South Africa to Namibia. The study observatories traverse four biomes, namely, Succulent Karoo, Nama Karoo, Savanna and Woodland (Fig. 1.1). The details with regard to geographic coordinates and full names of observatories are given in Appendix C.

Further aims of this study were to a) investigate the relationships between richness of five life forms of plants, namely phanerophytes (trees), chamaephytes (shrubs), hemicryptophytes (grasses), therophytes (annuals), and geophytes (plants with underground storage organs) and soil properties (infiltrability, clay + silt content, EC and pH); and b) to enhance understanding of properties affecting soil infiltrability, with a particular focus on the role of texture, EC and ESP.

Thesis Layout

This thesis consists of four chapters. The first chapter presents a literature review comprising of two parts. Firstly, it provides information on the relationships between plant richness and soil properties with a particular focus on infiltrability. Secondly, it highlights properties affecting soil infiltrability, with regard to the role of particle size, EC and ESP in crust formation. The second chapter presents an investigation into the relationships between richness of five life forms (phanerophytes (trees), chamaephytes (shrubs), hemicryptophytes (grasses), therophytes (annuals), and geophytes and soil properties (infiltrability, clay + silt content, EC and pH) along the BIOTA South transect, stretching from south western South Africa to Namibia. The third chapter focuses on the role of different soil particle size fractions in influencing infiltrability. A laser technique was used for particle size distribution measurements, which allowed for the determination of smaller particle size fractions than is customary with conventional laboratory techniques. The fourth chapter comprises an investigation into the role of soil EC and ESP in influencing infiltrability of soils of different texture. The final chapter consists of general discussion and conclusions. It integrates the major findings of this study and gives recommendations for the future research. Appendices provide detailed information on the methods used as well as additional figures for the data.

This study presents novel findings on relationships between plant richness and soil properties, and highlights the strong influence of subtle soil textural effects on soil infiltrability.

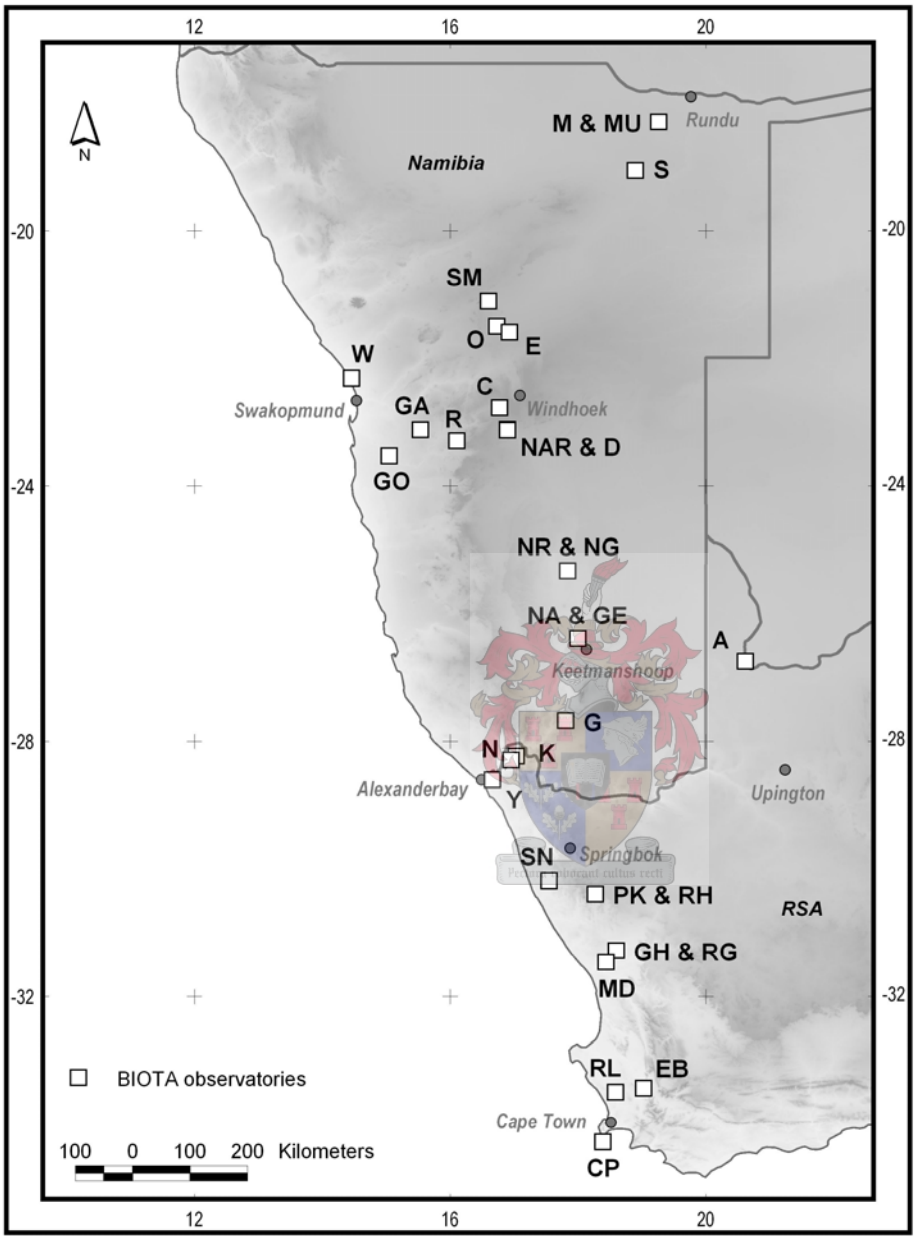


Figure 1.1. Location of study sites along the BIOTA South transect. Open squares indicate the positions of BIOTA observatories, with the abbreviated names.

CHAPTER 1: RELATIONSHIPS BETWEEN PLANT SPECIES RICHNESS AND SOIL PROPERTIES WITH PARTICULAR FOCUS ON INFILTRABILITY: A LITERATURE REVIEW

This chapter presents a literature review on the relationships between plant species richness and soil properties, with a particular focus on soil moisture. It highlights: a) the importance of crust formation in controlling soil moisture; b) the role of dispersion and flocculation processes in soil crust formation; and c) the properties affecting soil dispersion and flocculation.

1.1 Relationships between environmental factors and plant richness

A correlation between environmental factors and plant species richness (hereafter referred to as plant richness) has been reported (Lavers and Field, 2006). This is due to the profound effect extended by environmental factors on plant growth. No species are suited to every environment. Different plant species have different needs for moisture, soil nutrient content and amount of radiation received. Furthermore, environmental factors, such as energy and nutrient availability, control population growth. Conditions leading to an increase in growth rates of competing species result in monopolisation of resources by well-adapted species, and extinction of less-adapted species, which are unable to withstand competition. These processes are assumed to affect biodiversity negatively, i.e., reduce plant richness (Huston, 1979).

Numerous studies have reported hump-shaped relationships between plant richness and environmental factors (Grime, 1979; Tilman, 1982; Vermeer and Berendse, 1983; Janssens et al., 1998; Pausas and Austin, 2001). This pattern has been interpreted by a number of researchers (Grime, 1979; Huston, 1979; Austin, 1982; Tilman, 1988), whose theories can be summarised as follows. When resource availability is limited only a few species can survive these stressful conditions. As resource availability increases, more species can survive and hence plant richness rises. With a further increase in resource availability a few highly competitive species become dominant, leading to extinction of other, less-competitive, species. This competitive exclusion causes a decline in plant richness.

1.1.1 Factors which should be taken into account when investigating the effects of environmental factors on plant richness

Investigations into the relationships between plant richness and environmental factors have resulted in recommendations for conducting studies on richness-environment relationships. These can be grouped as follows: 1) the scale of the environmental gradient should be taken into account; 2) the patterns for different life forms of plants should be compared; 3) multivariate gradients, not single variables should be investigated, and 4) variables related to the growth of plants should be explored (Pausas and Austin, 2001).

1.1.1.1 Scale of environmental gradient

A consideration of scale is of critical importance when investigating plant richness in relation to environmental factors (Austin et al., 1996). Plant richness is controlled over large scales by climate, and over small scales by environmental heterogeneity (Lavers and Field, 2006). Climate affects the input of the resources needed for plant growth, such as moisture, solar radiation, and temperature, while environmental heterogeneity (topography, aspect, infiltrability) determines the number of "realized environmental gradient combinations" in a particular landscape (Lavers and Field, 2006). It is theorised that the greater the number of the combinations, the greater the number of niches for plant growth, which enables more plant species to co-exist (Huston, 1979; Tilman, 1982; Smith and Huston, 1989; Huston and De Angelis, 1994).

1.1.1.2 Life form richness

A number of researchers have reported that environmental "predictiveness" increases when plant life forms are investigated separately (Peet, 1978; Austin, 1980; Risherson and Lum, 1980; Olsvig-Whittaker et al., 1983; Minchin, 1989; Montana, 1990; Montana and Greig-Smith, 1990; Cox and Lawton, 1993; Pausas, 1994; Austin et al., 1996).

Austin et al. (1996) investigated the effect of environmental factors on life form richness (number of species within life forms) in Australia. Each life form showed a different response to the environmental predictors. Maximum richness of Eucalyptus species occurred at high temperatures, intermediate rainfall and radiation conditions on ridges with aseasonal rainfall

and intermediate nutrient levels. By contrast, maximum richness of rainforest species occurred at high temperatures, intermediate rainfall and low radiation in gullies with summer rainfall and high nutrient levels.

Minchin (1989) also found different patterns of richness for different life forms (namely, trees, shrubs, herbs, graminoids and ferns) in sub-alpine environments of Tasmania. These patterns related to two-factor gradients of soil drainage and altitude. In Minchin's (1989) research, trees attained their maximum richness on moderate to excessively drained sites, while shrub richness peaked on well-drained sites. The maximum richness of herbs was on poorly drained and waterlogged sites.

Gould and Walker (1999) investigated plant richness in Arctic riparian communities. They found that lichen richness decreased with increasing moisture, bryophyte richness generally increased with increasing moisture, and vascular plant richness showed no significant correlation with moisture.

Pausas (1994) also reported different patterns of species richness for different life forms (woody species, herbs, and mosses) in Pyrenean forests. Woody species had higher richness at intermediate N concentration, high Ca concentration and low altitude conditions. The most important variable explaining herb richness was radiation, with which a negative relationship was found. The maximum number of moss species was found at intermediate values of the moisture availability in alkaline soils.

These differences in life form responses to environmental parameters are reportedly related to the physiology of plants (Cody, 1991). Plant life forms reflect particular strategies for moisture utilisation (Yeaton and Cody, 1976; Phillips and Mac Mahon, 1981; Fowler, 1986; Yeaton and Esler, 1990), nutrient uptake and light interception. Therefore there should be a part of an environmental gradient, or the environmental niche, within which growth of each life form is favoured or restricted (Cody, 1986, 1989, 1991; Austin et al., 1996).

Wright (1992) suggested that different responses of life forms of plants to the environmental parameters might relate to rooting depths. Woody plants have exclusive access to a source of water relatively deep underground, while grasses use moisture available at shallow layers of soils. Sala et al. (1997) also reported differences in moisture utilization by grasses and shrubs

due to the differences in root systems. They found that shrubs and grasses in the Patagonian steppe used different water resources. Shrubs absorbed water exclusively from the lower layers, while grasses took up most of the water from the upper layers of the soil. Olsvig-Whittaker et al. (1983) investigated moisture utilisation by Raunkainer' (1934) classified life forms: therophytes, hemicryptophytes, geophytes and chamaephytes. They reported that desert therophytes exploited the top centimetres of the soil, and were abundant when surface soil moisture was relatively high. Hemicryptophytes, which are generally larger than therophytes, with deeper rooting systems, were more affected by soil moisture below the top few centimetres. Phanerophytes were most abundant in the warmer and moderately humid regions. Raunkiaer (1934) also reported that phanerophytes belonged to the comparatively moist regions with no long dry season. Cryptophytes predominated in warm-temperature regions with a long dry season, where moisture resources are more limited (Raunkiaer, 1934). In these regions clay accumulation in the bedding plains beneath rocks makes the available moisture harder to extract, but there is less evaporative loss. Because of larger root volume and reduced osmotic potential, the chamaephytes may extract this moisture more successfully than therophytes (Olsvig-Whittaker et al., 1983). Geophytes are particularly well adapted to growing in areas with long dry periods (Raunkiaer, 1934).

1.1.1.3 Effect of the combination of factors on plant richness

Plant richness is likely to be governed by two or more environmental factors (Margules et al., 1987; Pausas, 1994; Austin et al., 1996). Most environmental factors are complex (Whittaker, 1967). They involve a number of variables, only some of which exert a direct effect on the performance of species. A one-dimensional environmental gradient is meaningless unless defined in terms of other environmental conditions, and generalisations about single gradients are conditional upon other variables (Austin and Gaywood, 1994). Huston (1997) wrote that mistakes in conclusions about environmental factor's effect on species diversity might lie in "hidden treatments". These "hidden treatments" may be abiotic or biotic conditions, which are not taken into account during experiments. Pausas and Austin (2001) also emphasized the importance of multi-factor studies and the use of non-linear statistical techniques. The length of the nutrient gradient, the correlation with other nutrients present and the influence of pH on nutrient availability may all influence the shape of the response of plant richness to a nutrient (Pausas and Austin, 2001). Among the soil properties affecting plant growth, soil pH, electrical conductivity (EC) and moisture availability play the most important role.

1.1.2 Effect of the soil pH on plant growth and richness

Soil pH is an important factor for plant growth. It affects nutrient availability, nutrient toxicity, and microbial activity, as well as extending a direct effect on protoplasm of plant root cells (Larcher, 1980; Marschner, 1986). Grime (1973) and Gould and Walker (1999) found a unimodal relationship between plant richness and pH. In this model species richness declined towards both acidic and alkaline soils, which may relate to the availability and toxicity of soil nutrients.

In acidic soils (pH < 6) the essential nutrients such as calcium, magnesium, potassium, phosphorus and molybdenum are depleted or unavailable in a form useable to plants, which leads to nutrient deficiency (Larcher, 1980). Total nitrogen is also very low and the available nitrogen is limited to NH_4^+ form, because nitrification is inhibited (Marschner, 1986). In strongly acidic soils Al^{3+}, Cu^{2+}, Fe^{3+}, Mn^{2+} ions rise to toxic levels for the majority of plant species (Wolf, 2000). Sodic soils (pH > 8) tend to be deficient in Zn, Fe, Cu, K and Mn (Marschner, 1986). In this type of soil Bo can rise to phytotoxic concentration (Marschner, 1986).

Different plant species may not have the same range of adaptability and may require a narrow range of pH to survive (Larcher, 1980; Grubb, 1985; Leskiw, 1998). It has been reported that forest soils should be slightly acidic for nutrient supply to be balanced (Leskiw, 1998). Grassland species richness is highest at a soil pH range of 6.1-6.5 (Grime, 1973).

1.1.3 Effect of the soil salinity on plant growth and richness

Salinity affects yield (Ayers and Westcot, 1985) and germination rate of plants (Hayward and Bernstein, 1958) through an osmotic effect, specific ion effects, and changes in soil physical properties (Keren, 2000). The osmotic effect relates to the fact that plants extract water from the soil by exerting an absorptive force greater than that which holds the water to the soil (Ayers and Westcot, 1985). The more salt in water, the greater the osmotic potential and the more energy required by the plant to extract water. As a result, in soils with high salt concentration, plants extract less water than in soils with low salt concentration. Therefore, high salinity may reduce moisture availability to plants and result in plant dehydration (Ayers

and Westcot, 1985). In addition, reduced moisture availability diminishes nutrient uptake, which may further restrict plant growth (Allen et al., 1994). Due to the effect of salinity on moisture availability, climatic conditions (such as moisture, temperature, light) can greatly affect salt tolerance (Shannon, 1979). It has been reported that most crops can tolerate greater salt stress under cool humid than hot dry conditions (Keren, 2000).

High levels of salts can also result in ion toxicity and nutrient imbalance (Marschner, 1986). This usually relates to excess sodium and more importantly chloride ions, which negatively affect plant enzymes (Larcher, 1980). A high concentration of NaCl also reduces the uptake of important mineral nutrients, K and Ca, which further reduces cell growth, especially in roots (Larcher, 1980). In addition to the potentially toxic accumulation of Na^+ ions in plant tissue, a high Na concentration may also negatively affect soil physical conditions. It may, for example, increase dispersion of soil particles, and promote crust formation, which decreases water infiltration (McBride, 1994). High salt levels also lessen the uptake of several micronutrients, especially Fe (Wolf, 2000).

Due to the negative effects of soil salinity, plants can have the following physiological features: smaller stature with darker, more bluish foliage, occasionally brown leaf tips, leaf mottling, curling and chlorosis. A high chlorophyll content and thick cuticle tend to produce a bluish colour (Black, 1968). In woody species, salt damage can include late, stunted buds, small leaves and necroses in buds, roots, leaf margins, and shoot tips (Larcher, 1980).

Generally speaking, plant growth becomes restricted when the EC of a saturated paste extract of soil exceeds a critical value of 4 dS m^{-1}. However, some species are sensitive to salinity at even lower EC values. It has been reported that threshold concentrations for soil salinity beyond which crop yield is reduced is 1 dS m^{-1} (Ayers and Westcot, 1985). Although this is a general threshold value for all crops, this value will differ slightly for each particular species. This slight variation highlights differences in adaptation strategies between plant species.

Some species are better adapted to saline conditions as a result of “key characteristics” that allow them to survive in the presence of competitors (Grubb, 1985). These key characters are: salt-exclusion at the roots, salt sequestration in vacuoles, salt-secretion via glands, and inflated leaf hairs (Grubb, 1985). In woody species, for example, exclusion of Na^+ and Cl^- ions from plant roots is the most important mechanism for salinity tolerance (Allen et al.,

1994). Halophytes are able to eliminate excess salts by shedding plant parts heavily loaded with salts (Larcher, 1980). *Atriplex* and *Halimione*, for example, are able to collect Cl^- ions in vesicular hairs that die off and are subsequently replaced (Larcher, 1980). Other halophytes may have glands in the leaves and hair that are able to excrete salts to keep accumulation to tolerable limits (Larcher, 1980).

1.1.4 Effect of soil moisture on plant growth and richness

Water availability is reported to be one of the most important environmental parameters controlling plant richness (Lavers and Field, 2006). Its effect is even more profound in arid environments, where soil moisture is the major limiting primary resource. Vegetation structure in southern African savannas and grasslands is determined by moisture availability (Scholes et al., 1997), and precipitation is considered to be one of the most important factors affecting plant diversity (Cody, 1989). These observations can be explained by the fact that in semi-arid Africa, plant productivity is limited by moisture availability (Belsky, 1995). Higher moisture availability enhances plant growth and productivity, which in turn is likely to affect plant diversity for reasons discussed in section 1.1 above.

1.1.4.1 Reported findings on the relationships between the soil moisture availability and plant richness

Several investigations have been undertaken on changes in plant richness along moisture gradients, but to date no consistent general relationships have been found. A number of researchers reported a positive relationship between plant species richness and rainfall (Richerson and Lum, 1980; Knight et al., 1982; Gentry, 1988; O'Brien, 1993). Richerson and Lum (1980), for example, investigated the effect of annual rainfall on species diversity in California, and found rainfall to be the strongest single variable controlling total species diversity as well as tree and herb diversity. The effect of precipitation on shrub diversity was small, but also significant. Minchin (1989) also found a significant positive correlation between species diversity and moisture availability, while Leathwick et al. (1998) found that humidity is one of the most important predictors for biodiversity.

By contrast, Cody (1989, 1991) found negative relationships between moisture availability and biodiversity in North American deserts. He reported that life form diversity peaked in climates characterized by low rainfall, high temperatures, and low seasonality of these factors.

These conditions enabled the coexistence of the widest range of plant life forms and the highest numbers of species. Montana (1990) also found that maximum plant richness occured where water availability was low.

Contrary to these observations, some researchers have reported no correlation between plant richness and precipitation. Barbour and Diaz (1973) found no correlation between rainfall and species diversity in Arizona, USA and Argentina, and Currie and Paquin (1987) found a weak relationship between plant richness and precipitation.

1.1.4.2 Factors modifying the effect of soil moisture on plant richness

The contradictory findings regarding the water received and plant richness can potentially be attributed to factors that modify soil moisture. A number of scientists used rainfall as a measure for moisture availability (Barbour and Diaz, 1973; Richerson and Lum, 1980; Currie and Paquin, 1987). Soil moisture, however, depends not only on precipitation, but also on soil infiltration and runoff, factors which were not taken into account in the studies discussed above. Other factors influencing moisture availability that should also be considered include: landscape position, slope, soil structure and texture, seasonality of precipitation and temperature.

Peet (1978) reported that moisture effect on species diversity was modified by elevation in forest vegetation of the northern Colorado Front Range. At high elevation, the richest forests were on wet sites, and richness decreased toward the xeric end of the gradient. At middle elevations lowest richness was found near the central portion of the moisture gradient, and the highest diversity sites occurred near the moist end. With decreasing elevation the lowest diversity was observed at the mesic end of the gradient.

Sala et al. (1997) reported that plant richness was more influenced by soil texture than by rainfall, and suggested that soil texture has a large influence on the location at which water is stored. Fine textured soils store more water near the surface layers than coarse-textured soils. Therefore fine-textured soils are more favourable for grassy vegetation with shallow root systems, compared to woody vegetation with deeper roots.

The seasonality of precipitation also affects soil moisture availability. Precipitation falling during the cold season has a higher probability of being stored in deep soil layers, because evaporation is relatively low. In deep soil layers grasses are less effective because of

shallower root systems and therefore these conditions should favour woody plants. Areas with maximum precipitation during the warm season would have high evaporation and lower net water balance compared to the areas with precipitation during the cold season. These conditions should support grasslands (Sala et al., 1997).

Temperature can also modify the effect of moisture availability on plant biodiversity. Austin et al. (1996) in their research in New South Wales, Australia, found that at low temperatures, tree richness was constant along the rainfall gradient, while at high temperatures a humped response was observed, with the maximum richness occurring between 900 and 1200 mm rainfall.

Pausas (1994) used an integrative approach for an investigation of the relationships between moisture availability and richness of understorey of *Pinus sylvestris* forest in the eastern Pyrenees. He used a moisture index based on soil and site parameters (topographic position, slope, soil texture, stoniness and soil depth) and found a humped curve for moss species richness.

In summary, no generalizations regarding relationships between plant richness and soil moisture availability can be made without a multi-dimensional, environmental context, since no one relationship satisfactorily describes the variation in richness along a moisture gradient (Peet, 1978). Therefore, the interaction of different environmental factors modifying soil moisture availability should be considered. One of the most important factors modifying moisture availability is soil infiltrability. The infiltrability, as well as the factors affecting are discussed in the following chapter.

1.2 Soil infiltrability and crust formation

Soil infiltrability is defined as the infiltration rate resulting when water at atmospheric pressure is freely available at the soil surface, such as when the rainfall rate exceeds the ability of the soil to absorb water (Hillel, 1971). It is largely determined by surface crusting (Fox et al., 2004). A number of researchers reported that crusts form in two stages: physical dispersion of soil aggregates caused by the impact action of the raindrops, and a chemical dispersion (Agassi et al., 1981; Kazman et al., 1983; Shainberg and Letey, 1984). The dispersion can be initiated by swelling (Shainberg and Letey, 1984), which reduces soil pore sizes, and can result in blocking or partial blocking of the conducting pores (Quirk and Schofield, 1955). Rowell et al. (1969) and McNeal et al. (1966) also explain a decrease in

hydraulic conductivity (HC) by swelling.

Dispersion operates when the charged clay platelets, which are moving apart in the process of swelling or as a result of raindrop impact, have separated enough so that attractive forces are no longer strong enough to oppose repulsive forces and the platelets can move by an external force (Quirk and Schofield, 1955). Dispersed particles move down into the soil profile, where they lodge and clog the conducting pores thereby reducing infiltration (McIntyre,1958b; Frenkel et al., 1978; Shainberg and Letey, 1984). The importance of dispersion in affecting soil permeability has been recognized by numerous researchers (Frenkel et al., 1978, Pupisky and Shainberg, 1979; Shainberg et al., 1981a & b; Eghbal et al.,1996).

The result of the above processes is the formation of a surface seal (Duley, 1939; Radcliffe and Rasmussen, 2000; So, 2002; Le Bissonnais, 2003), which is a very thin layer (0.1-5 mm) at, or just below, the soil surface that forms due to the breakdown of soil aggregates and chemical dispersion of clay particles under raindrop impact. Once the seal dries out, it develops high soil strength due to the increased density of the layer and is called a crust (Radcliffe and Rasmussen, 2000). Surface crusts are characterized by greater bulk density, greater strength, narrower pores, and lower saturated conductivity than the underlying soil (McIntyre, 1958a; Shainberg and Singer, 1985; Hillel, 1998).

Once formed, a surface crust can greatly impede water infiltration (Shainberg, 1985; Moss, 1991a; Hillel, 1998). McIntyre (1958a) reported that a soil crust layer 0.1 mm thick reduced infiltrability by a factor of 1800 relative to a deeper layer. Crusting also reduces seedling emergence (Moss, 1991a; Eghbal et al., 1996; Radcliffe and Rasmussen, 2000), and increases runoff and soil erodibility (Singer et al., 1982; Rao et al., 1998; Le Bissonnais, 2003).

A number of physical and chemical properties affect crust formation. The physical properties include texture (Ben-Hur et al., 1985) and aggregate stability (Farres, 1978) and the chemical properties include soil sodicity and the electrolyte concentration in the soil solution (Oster and Schroer, 1979; Agassi et al., 1981; Shainberg et al., 1981a; Shainberg and Letey, 1984; Hillel, 1998; Levy, 2000; Mamedov et al., 2000; Laker, 2004). Interactions between these factors can modify their individual influence (Le Bissonnais, 2003).

1.2.1 Soil texture effect on infiltrability

Soil texture is viewed as one of the most important soil properties controlling infiltrability (Hillel, 1998; Miller and Gardiner, 1998; Shukla and Lal, 2002). This is related to the fact that saturated water movement through a soil profile is controlled by soil porosity, by layering of textural classes and by dispersion of soil particles that result in surface crusting.

Infiltrability depends on pores sizes and on the tendency of particles to clog pores. Water in soil is held as films on particles surfaces and in small pores. Coarse-textured, or sandy soils, have large particles sizes and more pores compared to fine-textured soils (Radcliffe and Rasmussen, 2000). Large pores allow water to drain by gravitational flow. Therefore in coarse-textured soils infiltrability will be faster than in fine-textured soils. In the fine-textured soils silt and clay particles can fill voids between sand grains and in this way restrict water movement through the soil, while small pores retain water by capillary forces, which further restricts water movement down the profile (Radcliffe and Rasmussen, 2000).

Layering of different particle size fractions of soils also affects infiltrability. Buried clay or dry sand layers near the surface can reduce infiltration rates. An unstructured buried clay layer usually has a lower hydraulic conductivity than an overlying coarse-textured layer and reduces infiltrability once the wetting front enters the clay layer. A buried dry sand layer under a fine-textured layer also reduces infiltrability, but through a different mechanism. The water at the leading edge of the wetting front may be under high tension and cannot enter the smallest pores in the sand layer (which are much larger than the largest pores in the layer above) until the potential at the wetting front increases beyond the water potential for the sand. Once the sand is saturated it no longer impedes flow, because hydraulic conductivity is high in the sand compared to the fine-textured layer above (Radcliffe and Rasmussen, 2000).

Dispersion of soil particles and crust formation is another mechanism through which soil particles control infiltration (Agassi et al., 1981; Shainberg and Singer 1985; Eghbal et al., 1996). During a rainfall event, soil aggregates break down and disperse. As a result of this a thin seal layer forms, which impedes infiltration. In the next section the role of dispersion will be discussed in greater detail.

1.2.1.1 Role of soil particle size fractions in crust formation

Dispersion and crust formation processes have been widely investigated, although there is to

date no clear conclusion as to which particle size fraction plays the most significant role in crust formation. It has been reported that silt plays a very important role in crust composition (Lemos and Lutz, 1957; Kowal, 1972; Gabriels and Moldenhauer, 1978; DePloey and Mucher, 1981; Moss, 1991a & b; Moss and Watson, 1991). Some researchers have published photographs showing silty surface layers (Duley, 1939; Evans and Buol, 1968; Norton, 1987). In a sequence of experiments (Moss, 1991a & b) showed that during runoff, silt particles of 10-50 μm were deposited as tightly packed bed-load sediments and formed a seal layer over a compacted layer. Very fine sand particles of 50-100 μm were transitional in behaviour, and 100-1000 μm particles were highly mobile in the air splash environment.

Moss (1991a) showed that susceptibility to crusting depended not only on the proportion of silt present, but also on its abundance relative to the fine sand (63-125 μm) fraction. In his studies the infiltration was greater in soils with the higher ratio of fine sand to silt fractions. Moss (1991a) also found a discontinuous layer, which comprised small patches of loosely packed coarse particles, mainly sand, to be an apparent component of the rain-impact soil crust. He explained his findings by saying that particles larger than 1000 μm are moved only with difficulty by large raindrops, while particles of 3000 μm diameter cannot be lifted at all. This finding was in accordance with Tarchitzky et al. (1984), who reported that overland flow removes relatively large quantities of clay and other fine material and leaves behind the heavy particles.

Some researchers have emphasized the importance of clay particles in crust formation. Ben-Hur et al. (1985) reported that in soils with low clay content (< 10 %) the amount of clay available to disperse and clog soil pores is limited and poorly developed seals formed. Tackett and Pearson (1965) and Evans and Buol (1968) stated that clay orientation played an important role in the crusting. Morin et al. (1981) explained how this orientation of clay particles into a continuous dense skin comes about during crusting, as a result of suction forces below the crust or seal. This suction mechanism results in a continuous build up of the crust out of the suspended clay particles. McIntyre (1958a & b) reported washing of fine particles beneath the so called ‘skin seal’ of 0.1 mm, and the formation of a ‘washed in’ layer comprised of tightly packed clay particles. This layer was responsible for the restriction of infiltration in his experiment, which was done on a horizontal soil surface. Moss (1991b) reported that the formation of a ‘skin seal’ or a compacted clay layer was not a feature of sloping soil surfaces, where particles of < 10 μm were removed by air splash and runoff flow.

Thus dispersed clay played no part in crust formation in Moss's experiments. Moss (1991b) suggested that clay particles could form a compacted layer in soils, where the silt layer was prevented from developing, and where there was no rain impact on the actual soil surface. He asserted that even then, clay particles would not pass more than 1 mm into soil pores.

Valentin and Bresson (1992) reported that both silt and clay particles can affect crust formation, and that the role of each depends on which type of crust formation process takes place. They distinguished "skeleton" (coarse particles) and "plasmic" (fine particles) components of soil crusts. In their review Valentin and Bresson (1992) distinguished three main classes of crusts: structural, depositional and erosion. These types of crusts reflect different structures and composition of size fractions. The formation of them depends on landscape position, on soil texture, on rainfall intensity.

1.2.1.2 Types of soil crusts

Structural crusts form as a consequence of the breakdown of aggregates under the beating action of raindrops, or under mechanical compaction (Valentin and Bresson, 1992). Such crusts can be divided into: slaking, infilling, and sieving subclasses. These subclasses have different vertical arrangement of textural particles. Slaking crusts consist of a thin layer with no clear textural separation between coarse particles (skeleton) and fine particles (plasma). These crusts usually form when soils contain 15-20 % of clay, which can result in air being entrapped and compressed during wetting (Valentin and Ruiz Figueroa, 1987). Infilling crusts display silt grains clogging the surface pores. Such crusts result mainly from the slow erosion of the top of the surface aggregates and the subsequent illuviation of the separated silt. Sieving crusts are made up of a layer of loose skeleton grains overlaying a plasmic layer. They exhibit three well-sorted layers: the uppermost layer is composed of loose coarse grains, the middle consists of fine, densely packed grains with vesicular voids, and the lower layer shows a high content of fine particles with reduced porosity (Valentin, 1991). This type of crusting mainly affects sandy and sandy-loam soils (Valentin, 1993). Sieving crusts are also referred to as "filtration pavements" or "layered structural crusts". Downward movement of clay through the coarse-grained top layer can be enhanced by the percolating water. Fine particles then accumulate and form the plasmic layer (Valentin and Bresson, 1992). Depositional crusts form when the soil surface is ponded by sediment water (i.e., a muddy suspension of dispersed particles that settles onto and into the soil surface and clogs its pores)

(Hillel, 1998). Depositional crusts can form when soil particles are translocated and deposited at a certain distance from their original location (Valentin and Bresson, 1992). Still depositional crusts form in standing water and develop where surface flow is hindered. The larger grains sink rapidly and form the bottom layer, whereas the finer grains deposit more slowly and form the top layer. Therefore still depositional crusts consist of densely packed and well-sorted particles the size of which gradually increases with depth.

Erosion crusts form as a result of erosion of structural crusts, when the plasmic layer of structural crusts becomes exposed the coarse particles of the top layer are removed by wind or overland flow (Valentin and Bresson, 1992). Then a thin surface layer enriched in fine particles (i.e., an erosion crust) forms.

1.2.2 Effect of soil exchangeable sodium percentage on crust formation

Soil sodium is considered to be one of the main soil chemical properties influencing crust formation (Agassi et. al., 1981; Levy and Van der Watt, 1988; Eghbal et al., 1996; So, 2002; Le Bissonnais, 2003; Laker, 2004). The amount of sodium in the soil exchangeable complex is usually presented as exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR) (Singer and Munns, 1996). The ESP is the relationship between exchangeable sodium cations and the sum of exchangeable cations. The SAR is the amount of sodium in the saturation extract. A soil's ESP and SAR are positively related, because a soil's solution cations and exchange cations are nearly always in equilibrium with each other (Singer and Munns, 1996).

The effect of sodium on soils has been widely investigated. It has been reported, for example, that high ESP may enhance chemical dispersion of soils, which leads to crust formation and decreases infiltration rate (Agassi et al., 1981; Shainberg et al., 1981a; Kazman et al., 1983; Shainberg and Letey, 1984; Du Plessis and Shainberg, 1985; Miller and Gardiner, 1998; Robinson and Phillips, 2001).

To understand how sodium alters soil structure, the hydration process, which takes place during rainfall, should be considered. Exchangeable cations are attracted to colloid particles, but when such particles are wet, water molecules get inbetween the negatively charged clay particles and exchangeable cations. The Van der Waal' forces that hold particles together

become weaker, and the hydrated ions move away from the surface, tending to diffuse randomly through the liquid (McBride, 1994). Exchangeable Ca^{2+} and Mg^{2+} are divalent cations and are strongly connected to the colloid surfaces. By contrast, Na^{+}, a monovalent cation, is loosely held and readily hydrates. Therefore Na-colloids disperse more easily than Ca- and Mg-colloids (Singer and Munns, 1996; So, 2002). For this reason a high ESP negatively affects aggregate stability of soils and promotes crust formation (Rengasamy et al., 1984). As a result of this dispersion, soil infiltration is restricted and erodibility is increased (Singer et al., 1982).

1.2.2.1 Factors modifying the effect of the exchangeable sodium percentage on crust formation

The effect of sodium on dispersion of soils is, however, not simple. There are differences between different soils and there is no single threshold value for the effect of ESP on soil dispersion (Laker, 2004). It has been reported, for example, that an ESP value of 15 % is a critical level above which soil structure could be negatively affected (US Salinity Laboratory Staff, 1954). Other scientists reported, however, that soil dispersion could occur at even smaller ESP values. Bloem (1992) and Bloem and Laker (1994) reported that soils of 2 % ESP were chemically dispersive.

These differences may be attributed to the fact that the effect of sodium on dispersion can be modified by soil clay content (Shainberg and Letey, 1984; Ben-Hur et al., 1985), clay mineralogy (Frenkel et al., 1978; Levy and Van der Watt, 1988; Stern et al., 1991; Levy et al., 1993; Laker, 2004), the presence of soil stabilising agents (such as sesquioxides and organic matter) (McNeal et al., 1968; Du Plessis and Shainberg, 1985; Thompson, 1986), and by the electrolyte concentration of the infiltration solution (Shainberg et al., 1981a; Shainberg and Letey, 1984).

1.2.2.1.1 Soil texture

A number of researchers reported that soils with high clay content are more sensitive to high ESP levels. McNeal et al. (1968) reported that the reduction in infiltration caused by an increase in exchangeable sodium concentration was greater for soils having higher clay content. Similarly, Frenkel et al. (1978) compared soils of 11 % and 32 % clay content, and found that the susceptibility of soils to disperse under sodic conditions increased with an

increase in clay content. Soils with high clay content have sufficient particle-to-particle contact points to form strong bonds when the soil dries, which can lead to the formation of a strong crust (Cary and Evans, 1974). Furthermore, the small mean pore size makes these soils more susceptible to pore blockage by swelling. By contrast, coarse-textured soils have relatively small number of contact points between soil particles, and a relatively large average pore size, which make them less susceptible to such swelling effects (Shainberg and Letey, 1984).

At low ESP levels, medium-textured soils have been reported to be particularly susceptible to crusting. Ben-Hur et al. (1985) reported that in soils with low ESP (< 3 %) medium textured soils (20 % clay) had greater crusting, and a lower infiltration rate than soils with a higher clay content (> 20 %). They explained that soil structure was more stable and the formation of crusts was reduced in soils with a high clay content. In soils with a low clay content (< 20 %), a limited amount of clay was available to disperse, and as a result, a poorly developed crust was formed.

1.2.2.1.2 The capacity of soil to release salt

Another factor, which can modify the ESP effect on soil dispersion, is the capacity of soils to release salt as a result of mineral dissolution. This salt release can change the electrolyte concentration of percolating solutions (Shainberg et al., 1971; Shainberg et al., 1981b) and thereby influence dispersion. Soils that release salt at a rate sufficient to maintain the soil solution concentration above the flocculation value of the clay will not disperse, and the infiltration of these soils will be affected only slightly by rainfall. By contrast, soils that do not release salts upon leaching will tend to disperse, and the infiltration will be very sensitive to the ESP of these soils (Shainberg et al., 1981a). 9

1.2.2.1.3 Soil mineralogy

Regarding mineralogy, the sensitivity of soil to crusting decreases as follows: smectitic > illitic > kaolinitic (Levy, 1988). According to Levy and Van der Watt (1988) the final infiltration rate of a kaolinitic soil with no smectite was only slightly affected by ESP. When smectite was present in a kaolinitic soil, the susceptibility of the soil to sodicity, as reflected by crust formation, increased. Frenkel et al. (1978) also reported that even small amounts of

smectitic clay (2 %) in kaolinitic soils can cause a sharp decrease in permeability. Similarly, Kazman et al. (1983) found that in smectitic soils seals can form even at low levels of ESP (e.g. 1 %).

An illitic soil was found to be more susceptible to sodicity and hence to crusting than any of the kaolinitic soils investigated (Levy and Van der Watt, 1988). According to their clay mineralogical status, soils can be subdivided into stable (containing no detectable amount of smectite) and unstable dispersive soils (containing some smectites) (Stern et al., 1991; Levy et al., 1993). Infiltration rate in stable soils is only slightly affected by ESP, whereas in unstable soils it significantly decreases at high ESP levels (Levy and Van der Watt, 1988; Gal et al., 1992). Semi-stable soils, with small smectitic impurities, may behave like stable or unstable soils depending on the ESP value: at ESP = 1 % they behave like the stable soils, and at ESP > 1 % they behave like unstable soils (Levy et al., 1988).

It has also been shown that clay-sized quartz and feldspar particles in South African soils are highly dispersible under mild mechanical shaking in distilled water, and that even phosphogypsum could not flocculate these inert materials (Bühmann et al., 1996). Bühmann et al. (1996) developed a hypothesis that "the marked susceptibility of silty soils to erosion is directly related to the chemically inert character of their dominant soil constituents, i.e., quartz and feldspar". Laker (2004) also attributed high dispersibility of soils from semi-arid regions to the significant quantities of clay-sized quartz.

1.2.2.1.4 Soil sesquioxides and organic matter

Du Plessis and Shainberg (1985) investigated the effect of sodicity on permeability of South African soils and found that differences in crusting behaviour of soils were better explained by the presence of sesquioxides and organic matter content than by clay mineralogy. Thompson (1986) reported similar findings, and showed that in highly weathered "red sesquioxic clay soil" even an ESP of 42 % did not cause dispersion. Sesquioxides and organic matter acted as stabilising agents for soil structure and prevented dispersion.

In conclusion, the relationships between ESP and soil sealing should be determined separately for soils that have been grouped on the grounds of other criteria, for example clay mineralogy or sesquioxides content. If the different groups of soils are pooled, no significant relationship

is found (Bloem, 1992).

1.2.3 Effect of soil electrolyte concentration on crust formation

Soil electrolyte concentration is one of the most important factors affecting infiltration (Hillel, 1998). In a stable clay suspension, dispersed particles collide frequently because of Brownian motion, but separate again because of diffuse-double-layer repulsion forces. The dominance of one type of force over another depends on electrolyte concentration (Hillel, 1998).

1.2.3.1 Effect of electrolyte concentration on soil dispersion

When the electrolyte concentration is below the flocculation value repulsive forces are dominant, the particles separate and remain apart from each other, resulting in soil dispersion (Shainberg et al., 1971; Oster et al., 1980; Shainberg et al. 1981a; Kazman et al., 1983; Shainberg and Letey, 1984). Crusting does not require high soil clay content, as a small amount of dispersed clay is needed to clog the pores. Therefore even sandy loam soils with a low clay content may be sensitive to sodic conditions at low salinity levels (Shainberg and Letey, 1984). This explains why coarse-textured soils can potentially have low infiltrability (Shainberg and Letey, 1984). Pupisky and Shainberg (1979) obtained an 80 % reduction in the HC of sandy soils having only 3.1 % of clay when leached with distilled water, while Felhendler et al. (1974) obtained complete sealing of a soil with 10 % clay content when leached with distilled water. Similar findings were obtained by Frenkel et al. (1978), Rowell and Shainberg (1979) and Shainberg et al. (1981a).

1.2.3.2 Effect of electrolyte concentration on soil flocculation

A high salt concentration in the soil solution results in a greater concentration of exchangeable cations adjacent to clay surfaces, which results in the clay particles cohering (i.e., flocculating) as opposed to dispersing (Shainberg and Letey, 1984; Singer and Munns, 1996; Hillel, 1998).). The minimum electrolyte concentration that causes flocculation is referred to as the "flocculation value" (Shainberg and Letey, 1984). This flocculation value is unique for each soil, and depends on clay mineralogy and on the tendency of soil to release salts when diluted (Shainberg and Letey, 1984).

Quirk (1978) reported that flocculation of the fine fraction of the soil is a prerequisite for

development of a stable soil structure, which results in stable macropores and high water infiltration. Conversely, Shainberg and Singer (1985) concluded that flocculation process can also play a role in crust formation. Shainberg and Singer (1985) distinguished two types of depositional crusts. In the first type, a crust formed as a result of flocculation of soil particles. This crust formed in soils with ESP < 5 %. The other type of crust formed as a result of clay dispersion. It formed in soils with ESP > 5 %, and lower electrical conductivity (EC < 0.3 dS m^{-1}) than in the flocculated soils.

Gypsum is often used to prevent dispersion of soil particles and enhance flocculation (Oster, 1982). It increases hydraulic conductivity by increasing the ionic strength of the percolating solution, and by replacement of exchangeable Na^{+} with Ca^{2+} cations (Loveday, 1976; Shainberg and Letey, 1984; Miller, 1987). A number of scientists reported that gypsum applied to the soil surface significantly increased infiltration (Kazman et al., 1983; Miller, 1987).

1.2.3.3 The modifying effect of the soil electrolyte concentration on the effect of exchangeable sodium percentage on crust formation

The electrolyte concentration of the soil solution is one of the most important factors modifying the effect of ESP on soils (Shainberg et al., 1981a; Levy, 2000). Sodic soils are prone to dispersion, and a low concentration of salts in an infiltration solution can magnify the dispersion process (Agassi et al., 1981; Shainberg et. al., 1981a; Kazman et al., 1983; Hillel, 1998; Agassi et. al., 1994). By contrast, a high electrolyte concentration decreases the negative effect of ESP (Quirk and Schofield, 1955; Oster and Schroer, 1979; Agassi et al., 1981; Shainberg et al., 1981a; Shainberg and Letey, 1984; Du Plessis and Shainberg, 1985).

The differences in critical values of ESP, above which dispersion occurs, can be explained by differences in the electrolyte concentration of the infiltration solution. The US Salinity Laboratory Staff (1954) reported that an ESP value of 15 % was a critical value above which soil structure was deleteriously affected. By contrast, McIntyre (1979) reported that an ESP of 5 % was a more appropriate value in their research. Shainberg and Letey (1984) explained these different finding by different electrical conductivity of infiltrating solutions. In the US Salinity Laboratory studies (1954) the electrolyte concentration was higher (3 meq L^{-1}) in comparison to McIntyre's (1979) study (0.7 meq L^{-1}). The higher salinity of the infiltration

solution in the US Salinity Laboratory studies prevented dispersion at higher ESP values. Shainberg et al. (1981a) results confirmed this suggestion. In their research, at an electrolyte concentration of 3 meq L^{-1}, the hydraulic conductivity decreased when the ESP value exceeded 12 %. If distilled water was used as an infiltration solution, then hydraulic conductivity decreased at smaller ESP values of 1-2 %.

1.3 Summary

Soil properties, such as water content, texture, EC and pH have a significant effect on plant growth, and may influence plant richness. Inherent infiltrability of the soil is of particular interest in semi-arid ecosystems, where moisture is limited. Infiltrability has been extensively investigated over the last few decades. These investigations revealed that soil particle size, EC and ESP play an important role in determining infiltrability. There are, however, still many unanswered questions with regards to which soil properties govern infiltrability under specific physico-chemical circumstances The present study consequently investigates a) the relationships between plant richness and soil properties, and b) the influence of a wide range of soil properties on inherent infiltrability. Investigation into this is presented in the following chapters.

CHAPTER 2: RELATIONSHIPS BETWEEN SPECIES RICHNESS IN SELECTED PLANT LIFE FORMS AND SOIL PROPERTIES

2.1 Introduction

Determining the drivers of plant species richness (hereafter referred to as plant richness) provides insights into ecological processes and information for conservation planning. Several theories have been advanced to explain the high level of speciation in the southern African region. These theories relate to factors limiting gene flow (i.e., geographical isolation, ethology, phenology, sterility barrier), as well as to factors driving disruptive selection (adaptation to fire, microhabitat, climatic and edaphic specialization) (Linder, 2003). Due to the complexity of these factors consensus on the major drivers of plant richness remains elusive (Austin and Gaywood, 1994; Huston, 1997; Pausas and Austin, 2001; Pausas et al., 2003; Lavers and Field, 2006). The generalizations about single gradients are conditional upon other variables (Austin and Gaywood, 1994). An investigation into some of the individual factors may nevertheless, provide some insights into the ecosystem processes and factors determining plant richness.

The present study focuses on the effect of some soil properties on plant richness. Soil has a particularly large influence on the composition and structure of terrestrial flora (Grime, 1973; Huston, 1980; Tilman, 1982; Weiher et al., 2004). Some studies have reported a positive relationship between plant richness and soil fertility (Goodland, 1971; Grubb, 1987; Wright, 1992). Other plant richness studies have highlighted the importance of edaphic conditions in terms of the different adaptation strategies of plants in different soil types (Goldblatt, 1979; Richards et al., 1997). Austin (2002) and Pausas et al. (2003) suggested that soil extends two main effects on plants: direct and resource effects. Direct effects relate to pH, for example, a property of the soil which is not consumed by plants but has a physiological effect on growth, while resource effects relate to nutrients and moisture availability. Heterogeneity of these properties is purportedly of major importance in explaining variations in plant richness (Weiher et al., 2004), because different species have a particular requirement for soil resources, and therefore should be restricted to places with a particular set of soil conditions.

Numerous studies have reported hump-shaped relationships between plant richness and environmental factors (Grime, 1979; Tilman, 1982; Vermeer and Berendse, 1983; Janssens et

al., 1998; Pausas and Austin, 2001). This pattern has been interpreted by a number of researchers (Grime, 1979; Huston, 1979; Austin, 1982; Tilman, 1988), and can be summarised as follows. When resource availability is limited only a few species can survive these stressful conditions and as a result plant richness is low. As resource availability increases, more species can survive and hence plant richness increases. With the further increase in resource availability a few highly competitive species become dominant, leading to extinction of other, less–competitive, species. This competitive exclusion causes a decline in plant richness.

One of the most important properties for plant growth is soil water content (Lavers and Field, 2006). Its effect is most evident in semi-arid regions, such as south-west Africa, where water is a major limiting primary resource (Cody, 1989; Scholes et al., 1997). Relationships between moisture availability and plant richness have been investigated by several researchers, but no clear relationships have emerged, possibly because of a paucity of theory underpinning these investigations. Effects of moisture availability on plant richness have often been surmised from rainfall data. Some studies (Richerson and Lum, 1980; Knight et al., 1982; O'Brien, 1993) have shown positive relationships between plant richness and rainfall, while others showed weak or no correlations (Barbour and Diaz, 1973; Currie and Paquin, 1987).

These contradictory findings may be attributed to factors modifying the effect of moisture availability, such as seasonality of precipitation (Sala et al.,1997), temperature (Austin et al., 1996), soil texture (Sala et al., 1997), elevation (Peet, 1978) and topography. Furthermore, plant richness is likely to be governed by several environmental factors (Margules et al., 1987; Pausas, 1994; Austin et al., 1996), which may obscure straight-line correlations. Scale is yet another aspect to consider when hypothesizing on factors influencing richness (Austin et al., 1996; Pausas and Austin, 2001; Lavers and Field, 2006). For example, on a large scale, moisture availability may be largely a function of rainfall and temperature, while on a small scale it may depend on soil runoff and infiltration.

One of the most important factors affecting infiltration is surface crusting (Fox et al., 2004). It is an integral parameter, which reflects such edaphic characteristics as soil texture (Morin et al., 1981; Moss, 1991a & b; Valentin and Bresson, 1992), mineralogy (Frenkel et al., 1978; Kazman et al., 1983; Stern et al., 1991; Levy et al., 1993), organic matter, electrical

conductivity (EC) and exchangeable sodium percentage (ESP) (Oster and Schroer, 1979; Agassi et al., 1981; Shainberg et al., 1981a; Shainberg and Letey, 1984; Levy et al., 1993; Hillel, 1998; Levy, 2000; Mamedov et al., 2000; Laker, 2004). Crusts restrict movement of water into the soil profile (Shainberg, 1985; Moss, 1991a; Hillel, 1998), restrict emergence of new seedlings (Eghbal et al., 1996; Radcliffe and Rasmussen, 2000), and increase runoff and soil erosion (Singer et al., 1982; Rao et al., 1998; Le Bissonnais, 2003). An index of soil crusting is therefore a useful parameter to consider when assessing soil effects on plant species growth and consequently richness.

Soil salinity and pH should also be considered in an investigation of plant growth and richness. Extreme saline conditions may result in nutrient toxicity related to excess sodium and chloride ions (Larcher, 1980; Marschner, 1986), as well as restricted moisture availability due to the increase in osmotic potential (Ayers and Westcot, 1985). The reduced moisture availability may decrease nutrient uptake by plants, which may result in nutrient deficiency (Allen et al., 1994). Extreme conditions of nutrient deficiency and toxicity may affect emergence and survival of new species, and in turn plant richness. Due to the effect of plant salinity on moisture availability, climatic conditions (such as precipitation and temperature) can greatly magnify the salinity effect (Shannon, 1979). It has been reported, for example, that most crops can tolerate greater salt stress under cool, humid conditions compared to hot, dry conditions (Keren, 2000).

Grime (1973) and Gould and Walker (1999) found a unimodal relationship between plant richness and pH. In this model plant richness declined towards both acidic and alkaline soils, which may relate to the pH effect on availability and toxicity of soil nutrients. In acidic soils essential nutrients, such as Ca, Mg, K, P and Mo are depleted or unavailable in a form useable by plants, while some ions such as Al^{3+}, Cu^{2+}, and Fe^{2+} may rise to toxic levels (Wolf, 2000). Alkaline soils tend to be deficient in N, Zn, Fe, Cu, and K, and may have toxic concentration of Bo (Marschner, 1986).

The importance of focusing on different life forms of plants when investigating the relationships between environmental factors and plant richness has often been emphasized (Peet, 1978; Austin, 1980; Pausas, 1994). Several studies have demonstrated that patterns of potentially maximal richness in relation to environmental gradients differed between plant life forms (Minchin, 1989; Pausas, 1994; Austin et al. 1996; Gould and Walker, 1999). This was

related to the fact that life forms reflect particular strategies for resource utilization (Yeaton and Cody, 1976; Phillips and Mac Mahon, 1981; Cody, 1986, 1989, 1991; Fowler, 1986; Yeaton and Esler, 1990; Austin et al., 1996), and therefore should have different ranges or niche spaces where their richness would be potentially maximal.

In this study, the relationships between soil properties, namely infiltrability, texture, EC, pH and richness of five life forms (phanerophytes (trees), chamaephytes (shrubs), hemi-cryptophytes (predominantly grasses), therophytes (predominantly annual herbs), and geophytes (predominantly bulbs and rhizomes) along a 1700 km transect in south-west Africa were examined.

2.2 Methods

2.2.1 Study area

The research was conducted at 18 study sites located along a transect stretching from the western seaboard of South Africa to Namibia (Fig. 1.1, Introduction). The scale of the investigation was large, encompassing four biomes, namely, Succulent Karoo, Nama Karoo, Savanna and Woodland, and formed a part of the biological observatory network of the BIOTA southern Africa ecological observation program (Schmiedel and Jűrgens, 2005; Krug et al., 2006). Land use at all sites was livestock husbandry, game farming or conservation.

Each site comprised 1 km^2 divided into 100 m^2 blocks. Composite soil surface samples were collected from 10 m^2 plots situated within the centers of the 100 m^2 blocks using a grouting trowel. Each composite sample comprised 12 sub-samples, each approximately 100 cm^2 and 2 cm deep. The number of composite samples taken from each site ranged from 6 to 20 and varied according to the priority of the site within the BIOTA South framework. Each composite sample presented a sub-site with a distinctive set of soil properties, and consequently each sub-site is independent of other sub-sites. A total of 313 samples were analyzed. A summary of climatic and soil features for each site is given in Table 2.1. Plant species data for each 10 m^2 plot were obtained from the BIOTA South database. These data were categorized into five life form categories using Raunkiaer's (1934) classification system: phanerophytes, chamaephytes, hemicryptophytes, therophytes, and geophytes.

Table 2.1. Summary of climatic and soil characteristics of each study site.

Biome	Site[1]	N	Mean T[2]	MAP[3]	Lithology/ parent material	Soil Types (WRB[4])
Woodland	M	20	22	500-550	sands and calcrete	Ferralic Arenosols
	MU	20	22	500-550	sands and calcrete	Ferralic Arenosols
	S	20	20-22	450-500	sands and calcrete	Ferralic Arenosols, Calcisols
Savanna	O	20	20-22	300-350	granites, schists/ deep loams, sand	Chromic Cambisols, Luvisols, Arenosols
	E	19	20-22	300-350	granites/ deep loams calcrete	Chromic Cambisols, Luvisols, Calcisols
Nama Karoo	NR	7	20-22	150-200	sandstones/ unconsolidated materials	Regosols, Cambisols
	NG	6	20-22	150-200	sandstones/ unconsolidated materials	Regosols, Cambisols
	GE	20	20-22	100-150	shale/ colluvium	Regosols, Cambisols, Leptosols
	NA	20	20-22	100-150	shale/ colluvium	Regosols, Cambisols, Leptosols
Succulent Karoo	K	18	18	30	granite	Durisols, Cambisols, Calcisols
	N	13	18	30	quarzite, schist, granite	Leptosols, Calcisols, Regosols
	Y	20	19	60	dune sands, schist	Arenosols
	RH	20	15	180	gneiss	Leptosols, Calcisols, Fluvisols
	PK	19	15	180	gneiss	Leptosols, Calcisols, Fluvisols
	SN	19	17	150	gneiss	Durisols, Cambisols, Leptosols
	GH	17	18	110	shale, shyllite	Cambisols, Leptosols, Regosols
	RG	17	18	110	shale, shyllite	Cambisols, Leptosols, Regosols
	MD	18	18	120	shale, shyllite	Cambisols, Leptosols, Regosols

[1] study site refers to Fig. 1.1; [2] mean annual temperature (°C); [3] mean annual precipitation (mm yr^{-1}); [4] world reference base.

2.2.2 Sample analyses

Soil samples were air-dried, sieved to < 2 mm, and subjected to the following analyses: soil infiltrability, water-dispersible clay and silt, EC and pH. A rapid laboratory method (Mills and Fey, 2004) was used for the estimation of infiltrability and inherent crusting tendency of soils. This method involves the leaching of an agitated 1:5 soil:water suspension through a soil column (1.4 cm diameter). A slight modification of the published method was used, namely that soils were loosely packed rather than compacted. This was done to enable comparison of infiltrability across a wide range of soil types. Mills and Fey (2004) found that the results obtained with their method showed a strong correlation with results obtained by using a laboratory rainfall simulation method, although infiltrability through the syringe was approximately 10 times greater than under rainfall simulation. Infiltrability through the syringe is therefore not directly comparable with infiltration in the field, but can provide an index of the inherent crusting tendency of the soil. This crusting tendency is a function of a number of soil properties, such as soil particle size distribution, EC, pH, and clay mineralogy. A major advantage of the syringe method (compared to laboratory rainfall simulation) is that a relatively small amount of soil and time is required to assess the inherent crusting status of a soil. In this method, all the main processes involved in crusting such as dispersion of clay, slaking of aggregates, deposition of fine material and mechanical energy input are accomplished. Therefore, the simulated crust has features of both depositional and structural crusts (Valentin and Bresson, 1992). Water-dispersible clay (< 2 µm) and fine silt (2-20 µm) were determined by sedimentation and pipette sampling (Soil Classification Working Group, 1991). This method is based on time of settlement of the dispersed particles in a 1 L soil suspension. Sum of the clay and fine silt content is presented as “clay + silt” in the text hereafter. Soil EC and pH were determined in 1:5 soil:water suspensions (Rhoades, 1982) The details of these methods are given in Appendix A).

2.2.3 Statistical analyses

Several statistical approaches were taken to elucidate relationships between richness of life forms of plants and environmental parameters. Principal component analysis (PCA) and Pearson correlation coefficients were a first step. It is noted, however, that multivariate and linear regression techniques have a number of limitations when used to analyze the relationships between biotic and abiotic parameters (Sokal and Rohlf, 1995; Guo et al., 1998). Firstly, multivariate principle component analysis does not provide quantified relationships

between parameters. Secondly, plant richness depends on a complex of factors, which can modify the effect of any single factor (Margules et al., 1987; Pausas, 1994; Austin et al., 1996). Consequently, relationships between plant richness and an environmental factor are not usually linear, but tend rather to present as a scatter of values, or relational envelopes (Fig. 2.1a & b) (Mills et al., 2006b). Such scatters cannot be described by linear relationships, because the assumption of homogeneity of variance would be violated (Sokal and Rohlf, 1995). The only meaningful feature of these relational envelopes may be a boundary line. The shape of this boundary line describes a biotic response to the abiotic parameter and shows ranges over which plant richness is either potentially maximal or predictably restricted. The potentially maximal expression is, however, not guaranteed if there are other limiting factors affecting a response variable (Mills et al., 2006b).

In the present study a segmented quantile regression was used to delineate the boundary lines. It is based on a principle that regression curves can be fitted to various parts of the distribution (or quantiles) of the response variable, which provides a more complete picture of the relationships between variables than mean relationships (Mosteller and Tukey, 1977). This method involves subdividing the data into segments (or classes) according to the independent variable (Koenker and Hallock, 2001). The selection of a number of classes and a quantile value involves some subjectivity. The objective was to achieve a balance between a sufficient number of classes and a sufficient number of data points within each class to accurately reflect the distribution of the response variable over the particular range of the independent variable. The boundary lines presenting 0.95 and 0.1 quantiles were calculated using MSExcel. These lines circumscribe an envelope in which 85 % of observations occur. The 0.95 and 0.1 quantiles (as opposed to say 0.99 and 0.1 quantiles) were selected in order to reduce the effect of outliers; and thereby enable the construction of a relatively smooth boundary line.

To construct the boundary lines the data were sorted in ascending order according to the independent soil variable and subdivided into 19-21 classes, with equal number of samples in each class (Appendix B shows the number of classes and samples for each soil variable). Mean soil variables and quantile values (0.95 and 0.1) were obtained for each class. The regression lines were fitted to the 0.95 quantile values. These regression lines were selected

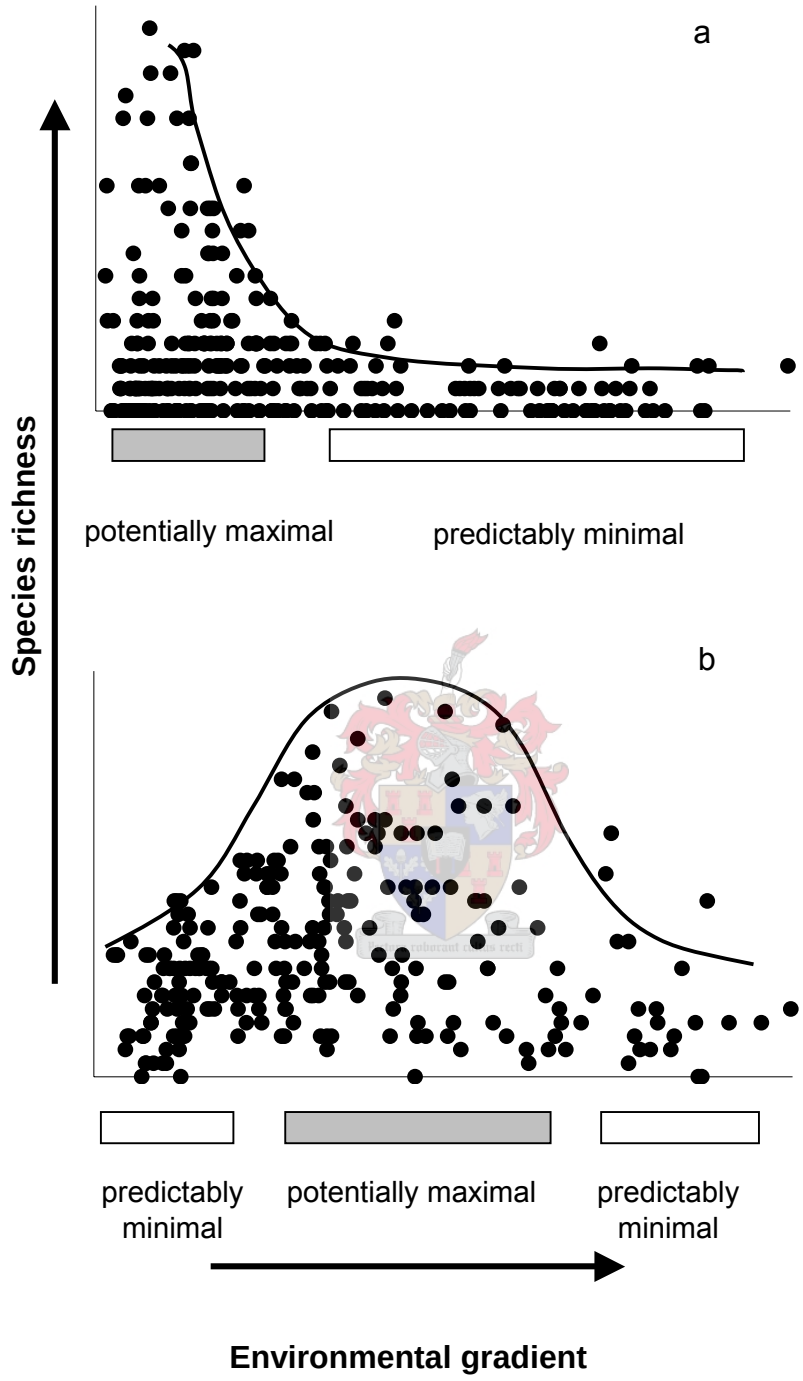


Figure 2.1. Hypothetical relationships between plant richness and soil properties showing a boundary line that divides ranges where plant richness is potentially maximal or predictably minimal: a) a negative wedge-shaped relationship; b) a hump-shaped relationship.

from power, exponential, straight-line, second order quadratic and logarithmic functions and chosen because they had the highest goodness of fit values (r^2), which provided a measure of the predictability of the relationship. In some cases, when no single function fitted the data, two functions were fitted to different parts of the data (normal and dotted lines) and r^2 values for these functions were obtained.

2.3 Results

Results of the principal component analysis (PCA) (Fig. 2.2) revealed that phanerophyte and hemicryptophyte richness showed similar responses to environmental parameters. It showed furthermore that richness of phanerophytes and hemicryptophytes were positively correlated with soil infiltrability, and negatively correlated with water-dispersible clay + silt content and EC. Chamaephyte, geophyte, and therophyte richness displayed different patterns to those of phanerophyte and hemicryptophyte richness, being positively correlated with water-dispersible clay + silt content and EC.

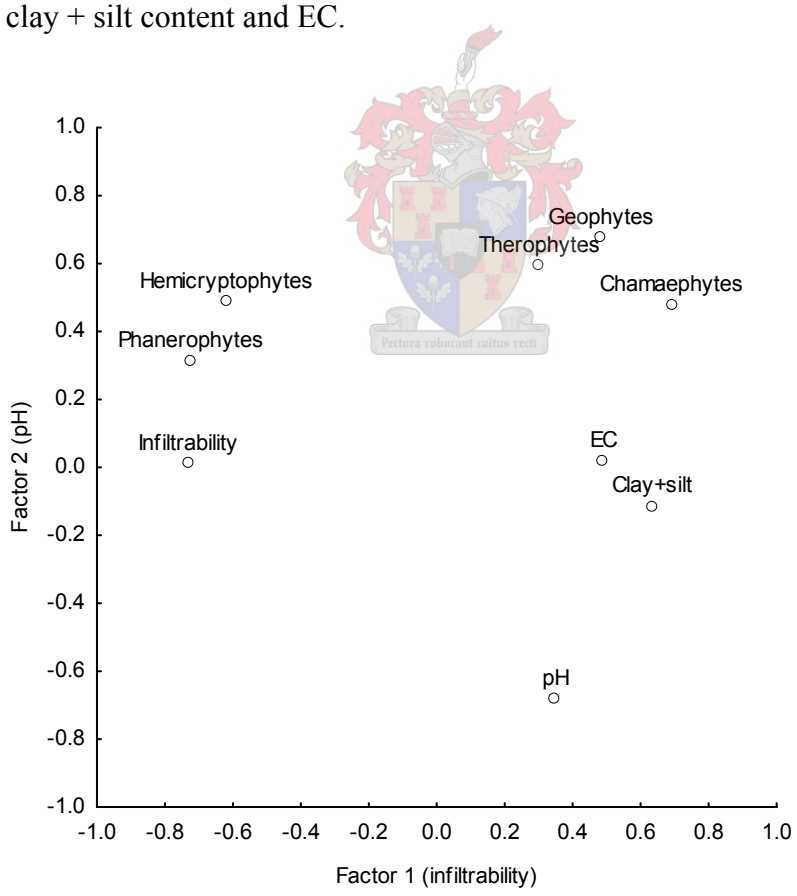


Figure 2.2. Principle component analysis results showing the relationships between richness of life forms and environmental factors.

Pearson correlation coefficients confirmed the PCA results and showed that rainfall and soil infiltrability were most significantly correlated with richness of life forms (Table 2.2). Richness of phanerophytes and hemicryptophytes were positively correlated, while richness of chamaephytes, therophytes and geophytes were negatively correlated with rainfall and infiltrability. Significant correlation was found between soil properties, in that water-dispersible clay + silt, EC and pH were all positively correlated with each other, and were negatively correlated with infiltrability (Table 2.3).

Table 2.2. Pearson correlation coefficients for the relationships between richness of plant life forms and environmental factors.

Life form	Pearson correlation coefficients for the relationships between species richness of life forms and environmental factors				
	Rainfall	Infiltrability	Clay+silt	EC	pH
Phanerophytes	0.73*	0.45*	-0.39*	-0.27*	-0.42*
Hemicryptophytes	0.71*	0.30*	-0.22*	-0.30*	-0.49*
Chamaephytes	-0.54*	-0.36*	0.27*	0.35*	-0.07
Therophytes	-0.23*	-0.24*	0.06	0.06	-0.07
Geophytes	-0.26*	-0.26*	0.08	0.12*	-0.17*

* indicates a significant correlation ($p < 0.05$) between richness of plant life forms and environmental factors.

Table 2.3. Pearson correlation coefficients for the relationships between soil properties.

Soil Property	Pearson correlation coefficients for the relationships between soil properties		
	EC	pH	Infiltrability
Clay + silt	0.31*	0.15*	-0.60*
EC		0.03	-0.20*
pH			-0.29*

* indicates a significant correlation ($p < 0.05$) between soil properties.

Richness of plant life forms exhibited distinctive envelope patterns in relation to soil infiltrability, water-dispersible clay + silt, EC and pH. Results obtained throught the relational envelope approach reveated that richness of phanerophytes and hemicryptophytes had positive wedge-shaped envelopes, with predictably minimal richness at low infiltrability and potentially maximal richness at high infiltrability (Fig. 2.3). By contrast, a negative wedge-shaped envelope was observed for richness of chamaephytes and geophytes, with minimal richness at high infiltrability and potentially maximal richness at low infiltrability (Fig. 2.3). Therophyte richness showed a hump-shaped envelope in relation to the infiltrability gradient, with richness being minimal at low and high infiltrability and potentially maximal at intermediate values of infiltrability (Fig. 2.3).

Patterns showing the inverse of those obtained for infiltrability were observed for the relationships between richness of life forms and water-dispersible clay + silt content of soils. Richness of phanerophytes and hemicryptophytes exhibited negative wedge-shaped envelopes. By contrast, richness of chamaephytes and geophytes showed positive wedge-shaped envelopes, although predictability for geophytes was relatively low (r^2 = 0.17). Therophyte richness showed a different pattern from the other life forms, with a hump-shaped envelope in relation to the water-dispersible clay + silt gradient (Fig. 2.4).

Richness of phanerophytes and hemicryptophytes exhibited negative wedge-shaped envelopes in relation to EC, with minimal richness at high soil electrical conductivity values (EC > 100 mS m^{-1}), and potentially maximal richness at soil EC < 100 mS m^{-1} (Fig. 2.5). By contrast, richness of therophytes and chamaephytes showed a positive wedge-shaped envelope with inevitably minimal values at soil EC < 20 mS m^{-1}, and potentially maximal values at soil EC > 20 mS m^{-1}. Richness of geophytes showed a neutral envelope with no apparent effect of soil EC on richness.

Richness of all life forms showed high predictability (i.e., relatively high r^2 values) in relation to soil pH. Richness of phanerophytes and hemicryptophytes showed a negative wedge-shaped envelope, with potentially maximal values at pH 5.0–7.0. Chamaephyte and geophyte richness showed a hump-shaped envelope, with potentially maximal values at pH 6.5–7.5. Richness of all life forms showed predictably minimal values at pH > 9 (Fig. 2.6).

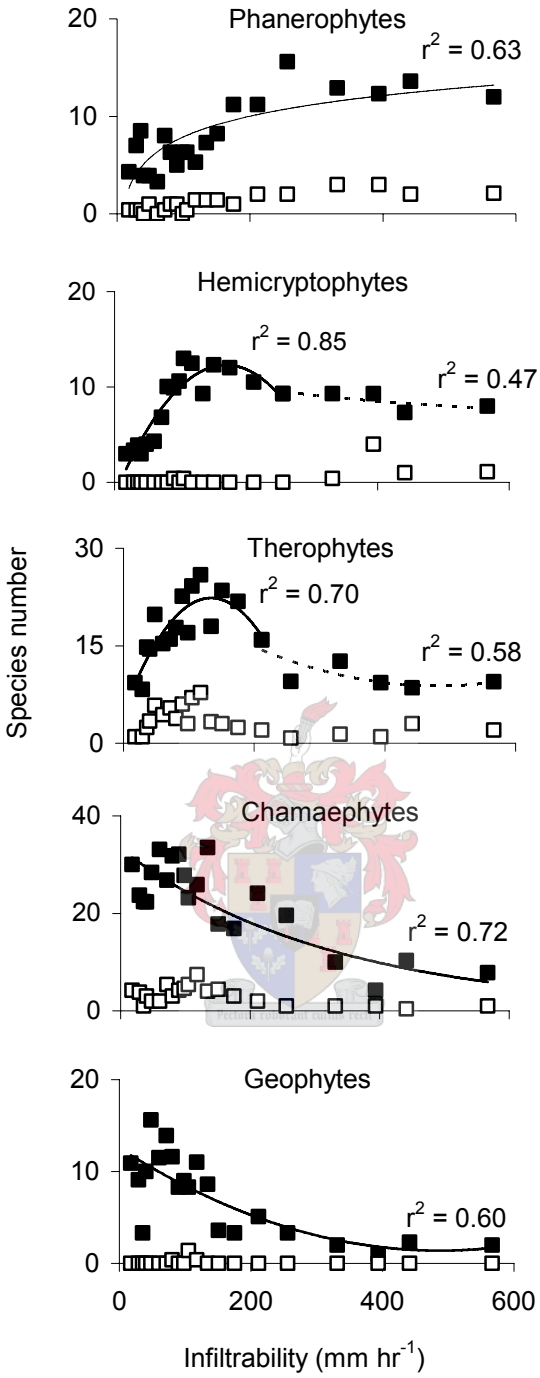


Figure 2.3. Relational envelopes derived from segmented quantile regression depicting the relationships between richness of life forms and soil infiltrability. Open squares depict the 0.1 quantiles, and filled squares depict the 0.95 quantiles for 21 classes of infiltrability. Within each class n = 15, except for the last class where n = 12. The r^2 of the best-fit regression lines are presented.

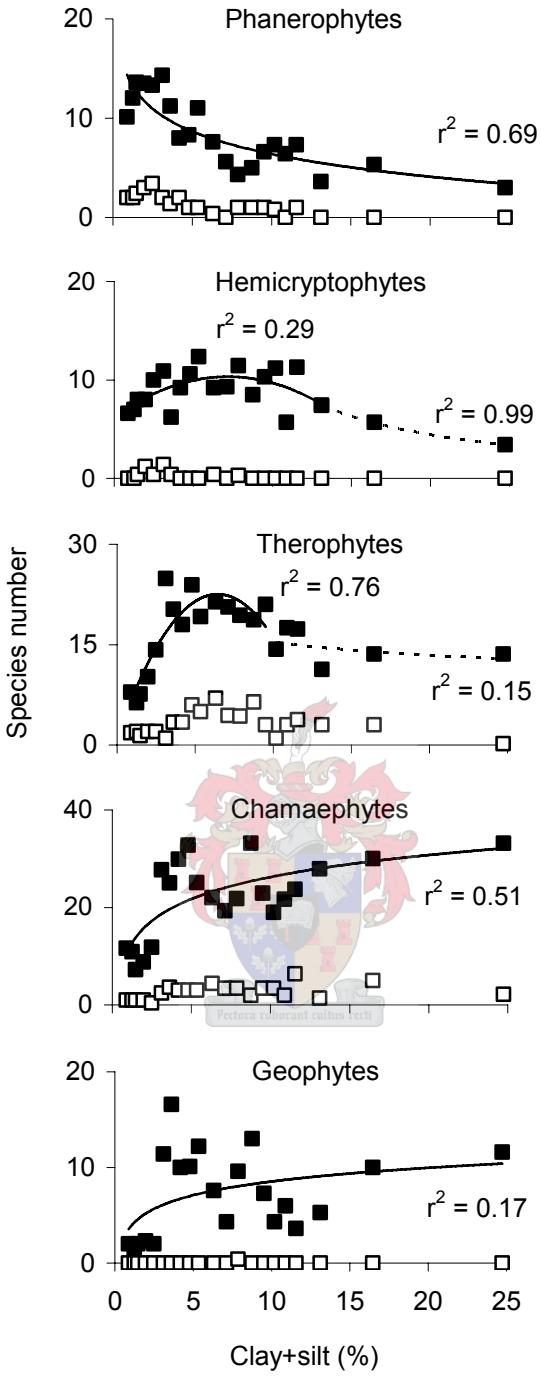


Figure 2.4. Relational envelopes derived from segmented quantile regression depicting the relationships between richness of life forms and water-dispersible clay + silt. Open squares depict the 0.1 quantiles, and filled squares depict the 0.95 quantiles for 21 classes of water-dispersible clay + silt. Within each class n = 15, except for the last class where n = 13. The r^2 of the best-fit regression lines are presented.

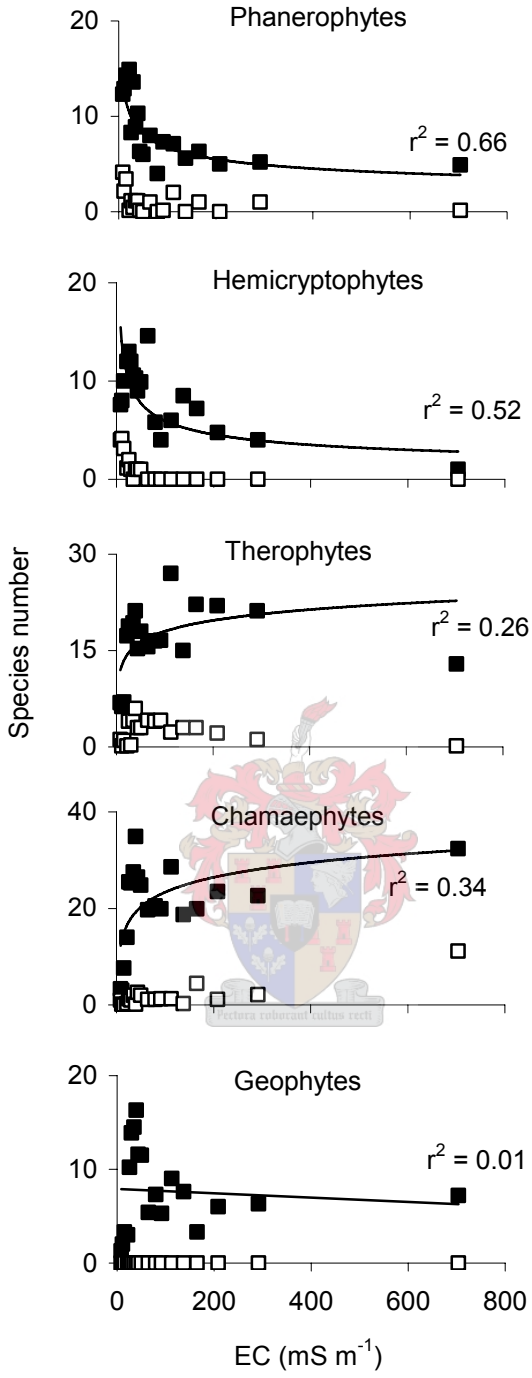


Figure 2.5. Relational envelopes derived from segmented quantile regression depicting the relationships between richness of life forms and EC. Open squares depict the 0.1 quantiles, and filled squares depict the 0.95 quantiles for 21 classes of EC. Within each class n = 15, except for the last class where n = 13. The r^2 of the best-fit regression lines are presented.

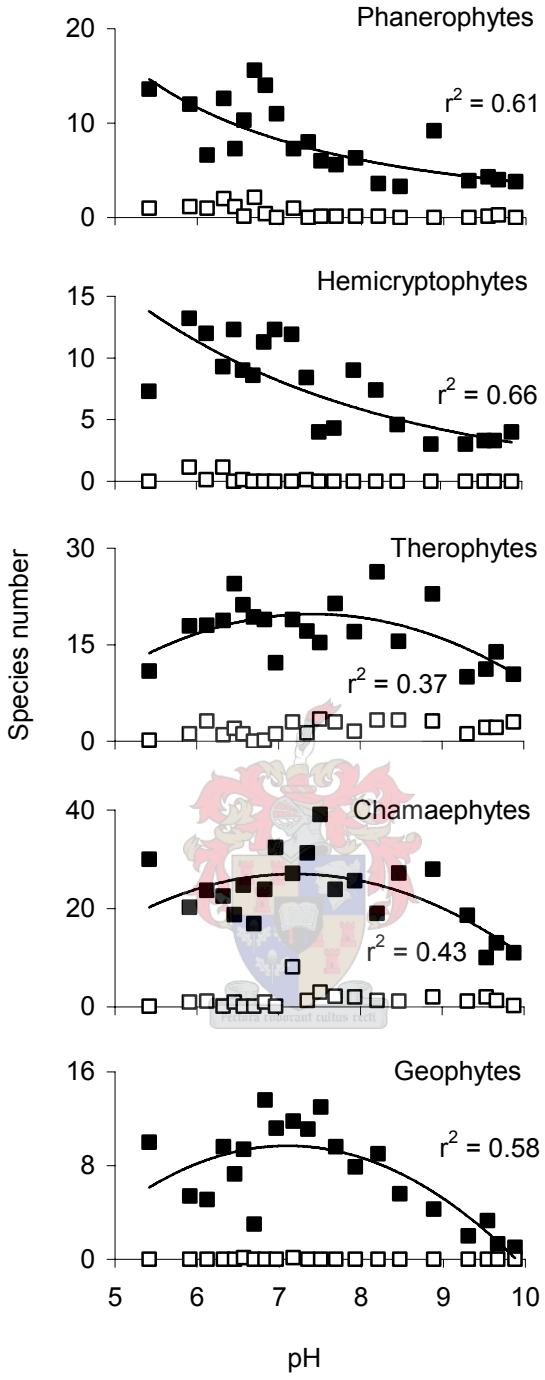


Figure 2.6. Relational envelopes derived from segmented quantile regression depicting the relationships between richness of life forms and pH. Open squares depict the 0.1 quantiles, and filled squares depict the 0.95 quantiles for 21 classes of pH. Within each class n = 15, except for the last class where n = 13. The r^2 of the best-fit regression lines are presented.

2.4 Discussion

The richness of plant species within any ecosystem is a function of numerous biotic and abiotic factors, which makes it difficult to investigate effect of a single environmental factor. Relational envelopes focus on an individual factor, but also reflect the result of numerous interactions and ecological processes, and are therefore an excellent analytical tool for such an investigation. The envelopes do not, however, necessarily reflect direct influences of the abiotic factors (Mills et al., 2006b). The patterns observed can potentially be related to the effect of the individual factors investigated; however, these factors may be merely correlated to the ultimately controlling factors. An advantage of the present study was that it was conducted at an unusually large scale, which enabled relationships between plant richness and soil properties to be investigated across a wide range of topography, climate, geology and soil type. Such an approach avoids the problem of localized effects and rather enables a search for general ecological rules that apply across biomes and continents.

The results of the present study showed that soil infiltrability, clay + silt content, EC and pH may be important properties to consider when explaining plant richness (Table 2.2). Ranges of these soil properties at which richness was potentially maximal were established. The explanation for the higher richness lies in accordance to the theories proposed by Grime (1979) and Huston (1979). It is suggested in this study that conditions conductive for growth may result in higher richness, as new species (appearing through the process of speciation) would have greater rates of survival under favourable conditions than under growth-restrictive conditions. Such restrictive conditions may relate to limited moisture availability, soil crusting, and nutrient toxicity related to pH and EC. It should be noted that the favourable conditions at which richness was potentially maximal varied between life forms. This finding was in accordance with numerous other studies (e.g. Richerson and Lum, 1980; Minchin, 1989; Pausas, 1994; Austin et al., 1996; Gould and Walker, 1999), and was attributed to different adaptation strategies of the different life forms.

Phanerophytes showed potentially maximal richness at high infiltrability and predictably minimal richness at low infiltrability (Fig. 2.3). Raukainer (1934), himself, noted that phanerophytes are best adapted to areas of high soil moisture. Woodward et al. (2004) also reported a positive correlation between precipitation and tree distribution, while, Wright (1992) suggested that the different responses of life forms to water availability may be related

to differences in root systems. Phanerophytes are plants with extensive root systems, which take up water from deep soil layers. In highly crusted areas, where the moisture infiltrability is restricted, growth of these plants may consequently be suppressed, unless they tap into groundwater resources. By contrast, conditions of high moisture availability may be more favourable for many phanerophyte species, and may result in higher richness.

Similar to phanerophytes, richness of hemicryptophytes and therophytes was restricted at low infiltrability values. Even though hemicryptophytes and therophytes absorb water from the upper layers of soils (Olsvig-Whittaker et al., 1983; Sala et al., 1997), their growth may be restricted in highly crusted areas, where clay accumulation at the soil surface makes extraction of soil water difficult (Olsvig-Whittaker et al., 1983). Furthermore, crusting may cause poor aeration and prevent germination and emergence of annual seedlings (Hayward and Bernstein, 1958), which may restrict richness of these life forms.

Chamaephytes, by contrast, are highly adapted to low infiltrability conditions because they have a relatively large root volume and a reduced osmotic potential, which promotes extraction of water (Olsvig-Whittaker et al., 1983). Geophytes are also well adapted to extended drought conditions (Raunkiaer, 1934), because they can store water in their below-ground organs. The better adaptability of these life forms may result in higher richness in dry conditions.

The patterns observed for chamaephytes and geophytes complied with Cody (1989; 1991), who suggested that plant richness should increase with severity of dry conditions associated with low precipitation. Mills et al. (2006a) also reported that diversity of Karoo plants was highest at low infiltrability. The explanation put forward for this pattern was that the rigorous physical environment results in a wide variety of adaptations, but no one adaptive solution is markedly superior over another (Cody, 1989). Mills et al. (2006a) suggested that plants in arid environments expend most of their energy to survive the water deficit, and that this reduces expenditure of energy on competitive interactions with neighbouring plants. In addition, in poorly permeable soils, minor changes in landscape may result in non-uniform distribution of moisture: run-off and run-on zones (Cowling et al., 1994; Ludwig et al., 1997). This creates high patchiness in moisture resources, which may also promote plant richness (Olsvig-Whittaker et al., 1983; Pausas and Austin, 2001; Mills et al., 2006a).

Cody's (1989) theory appears to contradict Grime's (1973) theory, which states that at extreme conditions of limited resource availability richness should be lower. The point here is that maximal richness should occur in areas where resources are limited, but not limited to the point where plant growth is greatly restricted, and only a few species can survive the harsh conditions. The finding of the present study contradicted Cody's (1989) theory in that limited moisture availability resulted in higher richness of only those forms which are highly adapted to arid conditions (i.e., chamaephytes and geophytes), while other life forms (i.e., phanerophytes and hemicryptophytes) did not show high richness at limited moisture (Fig. 2.3). This was probably related to the lack of such adaptations of the latter life forms to arid conditions.

The different patterns observed for different life forms (Figs. 2.3-2.6) may be also related to competitive interactions between species. Better adaptation of some life form to any particular conditions may suppress other life forms, which are less adapted and may open space for more competitive life forms. This may explain the pattern observed for therophytes, which was different from the other life forms and showed potentially maximal richness at the middle of the infiltrability and clay + silt gradients (Figs. 2.3 & 2.4). A possible explanation for this pattern is that in environments where other life forms are most adapted therophytes may be suppressed by intense competition.

It should be noted that richness allocated along soil gradients is only *potentially* higher. This means that in terms of particular soil property richness may be high over a certain range, however, it can be restricted over the same range by some other limiting factors, which may include any other soil property, as well as climatic conditions, species interaction, plant architecture, etc. Therefore soil properties do not guarantee higher richness; however, they may act as environmental filters by restricting plant richness. This can be seen in the geophyte data, which showed potentially maximal richness at low infiltrability and intermediate pH (Figs. 2.3 & 2.6). Low infiltrability tends to correlate with high pH, however, richness of geophytes was restricted at high pH. This means that potentially maximal richness of geophytes at low infiltrability conditions may be greatly restricted by high pH, and only soils having both low infiltrability and intermediate pH would have high richness of geophytes.

The relationships between richness of life forms and soil clay + silt content were the inverse of those found for soil infiltrability. Richness of phanerophytes and hemicryptophytes were

potentially maximal at low clay + silt content, while richness of chamaephytes was potentially maximal at high clay + silt content (Fig. 2.4). This finding may be attributed to the negative relationship between soil infiltrability and clay + silt (Table 2.3). At high levels of clay + silt content soil crusting tendency is higher, and as a result, soil infiltrability is lower (McIntyre 1958a & b; Moss, 1991a & b; Moss and Watson, 1991; Valentin and Bresson, 1992). Therefore, patterns observed for the relationships between soil clay + silt content and richness of life forms may also be a reflection of the effects of soil moisture availability on plants.

The effect of salinity on plant richness may relate to the adaptation of the life forms to salinity conditions. High salinity may negatively affect plant germination (Hayward and Bernstein, 1958). It may also result in reduced moisture availability by increasing osmotic pressure (McBride, 1994; Keren, 2000). In addition to reduced moisture availability uptake of essential nutrients, K^{+} and Ca^{+2} can also decrease which may reduce cell growth, especially at roots (Larcher, 1980; Allen et al., 1994). Furthermore, high levels of salts can result in ion toxicity and nutrient imbalance (Marschner, 1986). Low moisture and nutrient availability, as well as nutrient toxicity may restrict richness of life forms, which are not well adapted to high salinity conditions, as only few species are likely to survive such conditions. This was observed for phanerophytes and hemicryptophytes which had predictably minimal richness at EC > 100 mS m^{-1} (Fig. 2.5). Similar threshold concentrations were reported for crops by Ayers and Westcot (1985). The low adaptability of phanerophytes to saline conditions was also reported by Larcher (1980) who found that in woody species, high salinity induced late, stunted buds, small leaves and necroses in buds, roots, leaf margins, and shoot tips.

The effect of salinity, however, varies with different life forms. In the present study, chamaephytes and therophytes had potentially maximal richness at high soil salinity (Fig. 2.5). This suggests that these life forms have physiological adaptation strategies to high salinity. These strategies may include salt sequestration in vacuoles, salt-exclusion at the roots (Allen et al., 1994), salt secretion via glands, and inflated leaves (Grubb, 1985). Further research in this regard is warranted.

The high predictability (r^2) found for the life forms richness in relation to soil pH may be due to effects of pH on plant nutrient availability and toxicity (Larcher, 1980; Marschner, 1986). Even though tolerance to soil pH varies between plant species (Larcher, 1980; Grubb, 1985; Leskiw, 1998), a general pattern of low richness at pH > 9 for all life forms was observed

(Fig. 2.6). This may relate to the fact that nutrient deficiencies can be extreme in alkaline soils: HCO_3^- and CO_3^{2-} ions may reduce the availability of Fe, while high pH reduces the availability of Zn and Mg. Furthermore, high pH levels increase dissolution of Al-organic complexes, which may result in Al toxicity to plants (McBride, 1994). These factors may restrict plant growth and result in only a few, highly specialized species surviving under such extreme conditions.

Besides the direct effects which each soil property can have on plant growth, the observed patterns can also be attributed to the interrelationships of all soil properties (Table. 2.3). Soil infiltrability, clay + silt, pH and EC are all correlated with each other, which makes it difficult to distinguish the effect of any single factor. Fine-textured soils are prone to crusting, and usually have lower infiltrability values (Hillel, 1998). Soil EC is usually higher in these soils compared to the coarse-textured soils due to the higher exchange capacity and low leaching. The pH levels are also usually higher as a result of minimal leaching. Therefore, high levels of EC, pH and clay + silt content can be associated with arid conditions. Besides, dry climatic conditions can magnify the effect of salinity, as salinity negatively affects moisture availability, and plants growing on saline soils often appear to be suffering from drought (Keren, 2000). In contrast to fine-textured soils, coarse-textured soils usually have high infiltrability values and high leaching (Hillel, 1998). As a result, salts can be washed down the soil profile. This lowers the EC in topsoil layers. Consequently, higher richness of phanerophytes and hemicryptophytes in the present study can potentially be explained by the cumulative effect of high infiltrability, low clay + silt, and low EC, while higher richness of chamaephytes and geophytes may be related to both low infiltrability and high clay + silt.

2.5 Conclusions

The findings of the present study revealed that soil infiltrability, clay + silt, EC and pH are likely to be of particular importance in explaining plant richness. The relational envelope approach enabled determination of the ranges along which particular life form richness was potentially maximal or predictably restricted. These ranges differed between life forms, which was attributed to the different adaptation strategies possessed by the life forms to soil conditions. Conditions favourable for growth of a particular life form may enable higher survival of new species appearing through a process of speciation. Phanerophytes and hemicryptophytes may be better adapted to high moisture availability, which could result in

higher richness of these life forms at high infiltrability and low clay + silt. By contrast, chamaephytes and geophytes may be better adapted to arid conditions, and showed higher richness at low infiltrability, and high clay + silt content. The contrasting patterns found between clay + silt and infiltrability effects may be explained by the negative correlation found between these variables. High clay + silt content tend to promote crust formation and restrict infiltrability. Patterns for therophytes differed from the other life forms, and showed higher richness at intermediate infiltrability and clay + silt. This was speculatively attributed to the suppression of therophytes by life forms which are better adapted and therefore more competitive at particular soil conditions (e.g. chamaephytes at low infiltrability and phanerophytes and hemicryptophytes at high infiltrability). The life forms showed different ranges of potentially maximal richness along EC and pH gradients and all life forms showed predictably minimal richness at pH > 9, which may be related to the EC and pH effect on nutrient availability and toxicity.

The intricacy of their interrelationships between soil properties makes it difficult to distinguish which one has the most significant effect. Soil infiltrability is negatively correlated with clay + silt, EC and pH, and therefore the patterns observed can be related to the effect of any individual factor, or to the effect of some other ultimately controlling factor with which this individual factor is correlated.

It should be noted that the present study determined the ranges along soil gradients where richness was only potentially maximal. This means that in terms of the investigated soil property richness may be maximal, but if some other factors play a controlling role, richness can be restricted. These factors may include some other soil property, climatic conditions or interaction between species, which were not investigated in the present study. The complexity of the factors determining plant richness makes it difficult to include all relevant factors in a single study. The investigation into the selected factors of this study, although not all encompassing, does, however, provide insights into ecosystem processes. The relational envelope approach was particularly useful in this regard because it separates the influence of one factor from myriad other influences.

CHAPTER 3: RELATIONSHIPS BETWEEN SOIL PARTICLE SIZE FRACTIONS AND INFILTRABILITY

3.1 Introduction

Soil infiltrability has a large influence on plants in agricultural and ecological systems in semi-arid areas and merits further study. Soil texture is one of the main properties controlling infiltrability (Hillel, 1998; Miller and Gardiner, 1998; Shukla and Lal, 2002). It affects water movement by influencing porosity, layering of textural classes (Radcliffe and Rasmussen, 2000), and soil crusting (Agassi et al., 1981; Shainberg and Singer 1985; Eghbal et al., 1996). Surface crusts in particular can greatly reduce infiltrability (Shainberg, 1985; Moss, 1991a; Hillel, 1998) and increase runoff as a result (Rao et. al., 1998; Le Bissonnais, 2003). McIntyre (1958a), for example, reported that a 0.1 mm thick crust layer reduced infiltrability by a factor of 1800 relative to a deeper layer.

Despite a large body of research on the process of crusting, it is not clear which particle size fraction plays the most important role in crust formation. The importance of silt particles has been widely acknowledged (Lemos and Lutz, 1957; Kowal, 1972; Gabriels and Moldenhauer, 1978; DePloey and Mucher, 1981; Moss, 1991a & b; Moss and Watson, 1991). Moss (1991a) has also noted that loosely packed coarse particles of > 1000 μm can be a component of rain-impact soil crusts. The role of clay in crust formation remains, however, in dispute. Some researchers emphasize the role of clay dispersion in reduction of infiltrability. McIntyre (1958a & b) noted, for example, that under rainfall conditions soil aggregates break down and become compacted, forming a so called ‘skin seal’ surface layer, while dispersed clay particles are washed 1 mm down beneath the surface layer and are deposited in the voids, blocking pores and further restricting infiltrability. This finding was corroborated by Agassi et al. (1981), Ben-Hur et al. (1985), Shainberg and Singer (1985). Tackett and Pearson (1965) and Evans and Buol (1968) have, in addition, emphasized the role of clay orientation, whereby suction forces at the surface of the crust result in the orientation of clay particles into a continuous dense skin (Morin et al., 1981). By contrast, Moss (1991a) found no significant role of clay in crust formation. Valentin and Bresson (1992) focused neither on clay nor on silt particles, but distinguished a ‘skeleton’ and ‘plasma’ component in soil crusts, where fine ‘plasmic’ particles fill in pores formed by coarse ‘skeletal’ particles, and in this way restrict infiltration.

The objective of this study was to investigate which particle size fractions had the greatest effect on infiltrability. This information is important for understanding soil moisture dynamics, and for predicting the tendency of different soils to crust. In this particular study, a laser technique was used for particle size determination, which allowed for the determination of a greater number of particle size fractions than is possible with conventional laboratory techniques. Results from the laser and laboratory techniques were compared.

3.2 Methods

3.2.1 Data collection and analyses

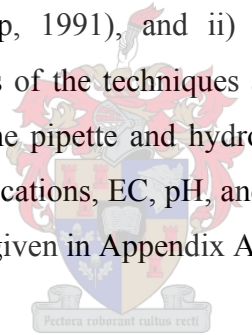
The details of the study area, and collection and preparation of samples for laboratory analyses are given in Chapter 2. Soil infiltrability and particle size distribution were determined on a total of 177 soil samples. A rapid syringe method (Mills and Fey, 2004) was used for measuring soil infiltrability through simulated crusts. Such crusts possess features of both structural and depositional crusts. According to Mills and Fey (2004), results from the syringe method correlate strongly with laboratory rainfall simulation. The infiltrability measured is not, however, directly comparable with infiltrability in the field, but provides an index of the inherent infiltrability of soil (Mills et al., 2006b). This index of inherent infiltrability will be referred to as 'infiltrability' hereafter. The soil infiltrability measurements followed the procedure given in Chapter 2 with slight modification, namely, that the infiltration solution in syringes was kept at a 7 cm level. This was done to maintain a constant hydraulic head.

A laser technique was used for water-dispersible particle size determination. The advantage of this technique compared to conventional laboratory techniques is that it is a faster procedure, less prone to human error, is more precise and it allows determination of narrower intervals of soil particle size fractions (Levy et al., 1993). A High Definition Digital Particle Size Analyser, Saturn Digitizer 5200 machine coupled with a Pentium IV computer was used. Samples in a 1:5 soil:water ratio were shaken thoroughly for 5 minutes prior to the analyses. The suspensions were then transferred into a machine chamber filled with distilled water. Samples were subsequently pumped continuously from the chamber between parallel glass lenses where the laser beam was intercepted. The particle size distribution was calculated from the angle distribution of the scattered light intensity collected by the detector. The angle

of diffraction is inversely proportional to particle size and the intensity of the diffracted beam at any angle is a mean of the projected areas of particles of a specific size. Signal from the detector was transmitted to the computer where data was fitted to a model of the particle-size distribution.

The particle size fractions were determined at the following intervals (given in μm): < 2, 2-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-100, 100-120, 120-200, and > 200. The United States system (Skopp, 2000) is used here for fraction classification. In this system the particle size fractions comprise the following size intervals (given in μm): clay (< 2), fine silt (2-20), coarse silt (20-50), very fine sand (50-100), fine sand (100-250), medium sand (250-500), coarse sand (500-1000) and very coarse sand (1000-2000).

The laser technique results for soil clay (< 2 μm) and fine silt (2-20 μm) fractions were compared with two laboratory techniques: i) water-dispersible fractions by pipette sampling (Soil Classification Working Group, 1991), and ii) total calgon-dispersed fractions by hydrometer (Day, 1965). The details of the techniques are given in Appendix A. A total of 173 samples were analyzed using the pipette and hydrometer techniques. The 177 samples were also analysed for exchangeable cations, EC, pH, and organic carbon (OC). Details of the methods used for these analyses are given in Appendix A.



3.2.2 Statistical analyses

A relational envelope approach discussed in Chapter 2 was used for the data analyses. A segmented quantile regression (Koenker and Hallock, 2001; Beirlant et al., 2004) was used for delineating boundary lines showing 0.95 and 0.1 quantiles. For the construction of boundary lines, data were sorted in ascending order according to the soil fraction content and subdivided into 18 classes, with 10 samples in each class. Mean soil fraction content values were obtained for each class. Quantiles (0.95 and 0.1) were obtained for infiltrability values in each class (see Appendix B4). For 0.95 quantiles, power boundary lines for soil fractions of < 120 μm size, and exponential boundary lines for soil fractions of > 200 μm size were plotted. These functions were selected from power, exponential, straight-line, second order quadratic and logarithmic functions, and were chosen because they had the highest goodness of fit values (r^2). The same procedure was followed to investigate the relationships between infiltrability and soil clay and fine silt fractions determined by the three different techniques

(i.e., laser analyser, hydrometer and pipette sampling), the only difference being that the x axis data was subdivided into 17, not 18 classes (see Appendix B6).

A Student's t-test was used for comparing the clay and fine silt mean values obtained by using different techniques. Pearson correlation coefficients were also determined for the relationships between infiltrability and clay and fine silt content determined by different techniques. These correlation calculations were performed (despite violations of the assumption of homogeneity) of variance by way of comparison with the quantile regression approach.

3.3 Results

Data for the particle size fractions content determined with the laser technique are given in Appendix B3. Relationships between soil infiltrability and narrow intervals of particle size fractions obtained with the laser technique are presented graphically as 0.95 and 0.1 quantile values (Figs. 3.1 & 3.2). Figures 3.1 & 3.2 also show regression lines fitted through the 0.95 quantile values, equations of these lines, and their goodness of fit values (r^2). Infiltrability was potentially maximal in soils with less than ~ 2 % in the < 50 µm size fraction (i.e., clay and silt) (Fig. 3.1a-f) and with less than ~ 5 % in the 50-100 µm fraction (very fine sand) (Fig. 3.1g-h). When the content of these fractions was above these threshold values (shown as dotted lines in Fig. 3.1 & 3.2) infiltrability was predictably minimal.

The 0.1 quantiles of the < 70 µm fractions (clay, fine and coarse silt, and very fine sand) increased markedly when the content was below ~ 2 % (Fig. 3.3). The > 70 µm fractions showed different patterns. They had low infiltrability values even at contents below 2 %.

The 100–120 µm fraction showed a similar pattern to the < 100 µm fraction, and at greater than ~ 5 % of this fraction infiltrability was predictably minimal (Fig. 3.2a). Infiltrability did not show a clear relationship with the 120-200 µm size fraction (Fig. 3.2b). Ratio values for the 120–200 µm fraction content in relation to the < 120 µm fraction, as well as the > 200 µm fraction, were instructive. Relationships for infiltrability and these ratio values are presented graphically as scatter plots (Fig. 3.4a & b).

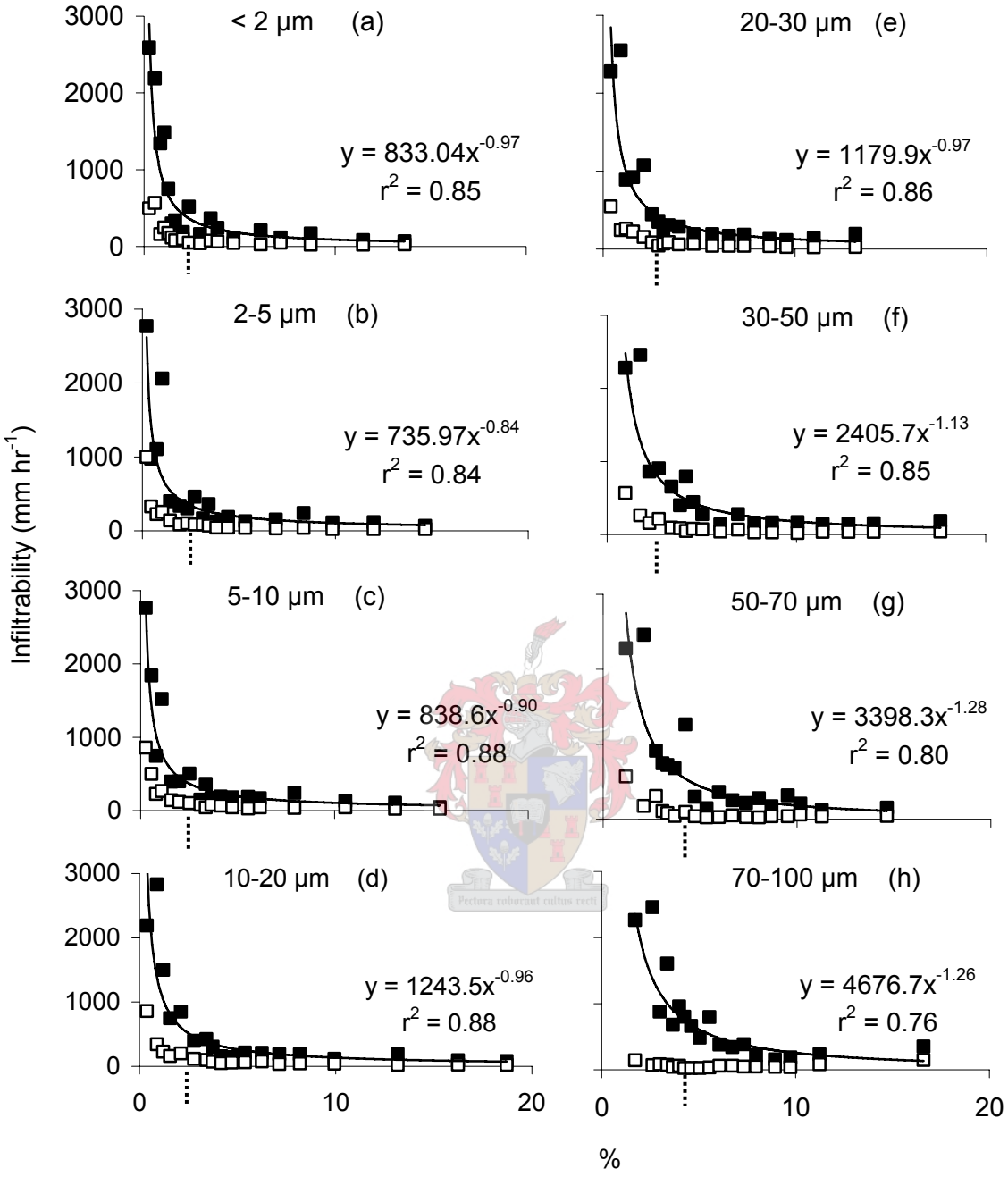


Figure 3.1. Relational envelopes derived from segmented quantile regression depicting the relationships between infiltrability and the content of soil fractions: a) clay (< 2 µm); b) fine silt (2-5 µm); c) fine silt (5-10 µm); d) fine silt (10-20 µm); e) coarse silt (20-30 µm); f) coarse silt (30-50 µm); g) very fine sand (50-70 µm); and h) very fine sand (70-100 µm). Open squares depict the 0.1 quantiles, and filled squares depict the 0.95 quantiles for 18 classes of each soil fraction. Within each class n = 10, except for the last class where n = 7. The formula and r^2 of the best-fit regression lines are presented.

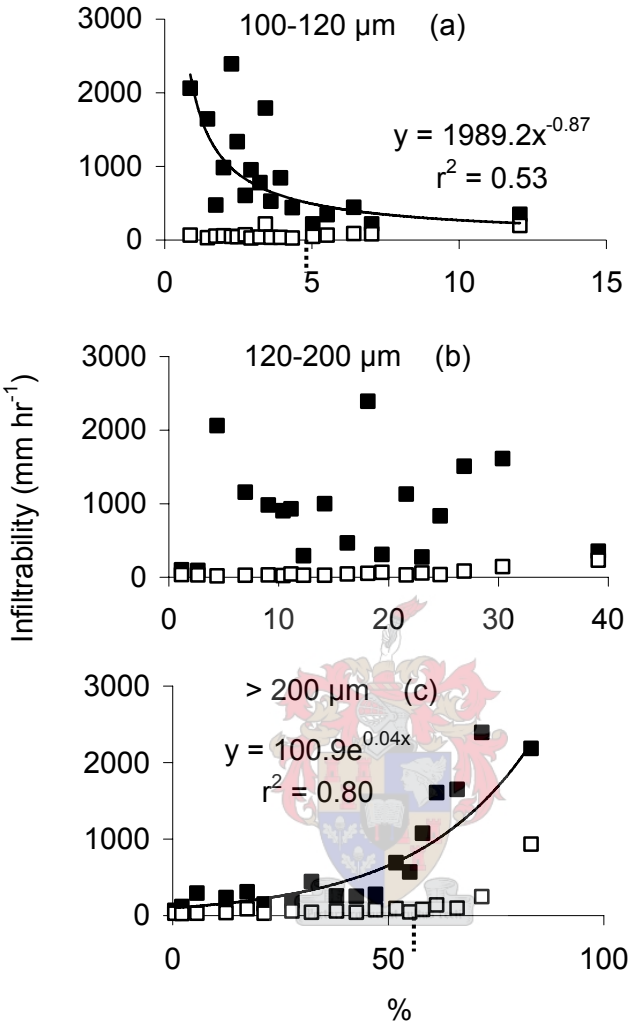


Figure 3.2. Relational envelopes derived from segmented quantile regression depicting the relationships between infiltrability and the content of soil fractions: a) fine sand (100-120 µm); b) fine sand (120-200 µm); and c) fine, medium, and coarse sand (> 200 µm). Open squares depict the 0.1 quantiles, and filled squares depict the 0.95 quantiles for 18 classes of each soil fraction. Within each class n = 10, except for the last class where n = 7. The formula and r^2 of the best-fit regression lines are presented.

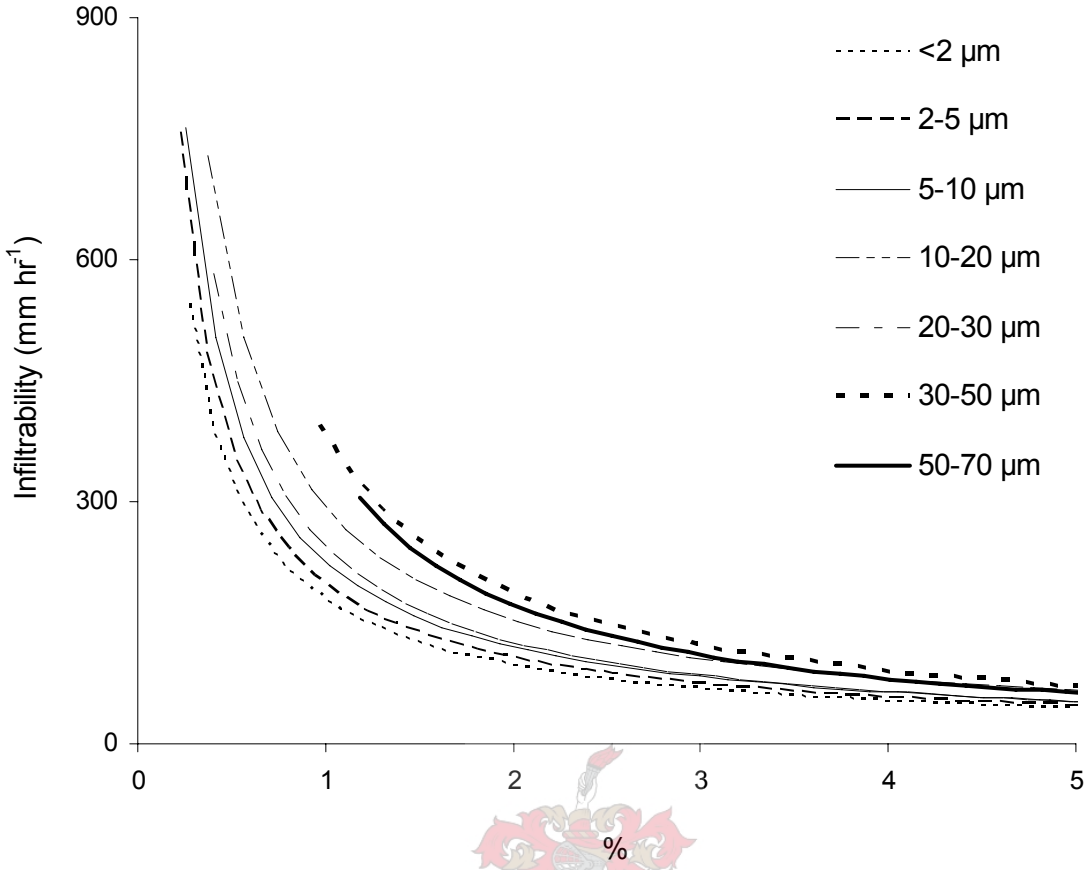


Figure 3.3. The relationships between infiltrability and the content of soil fractions of different size. Power regression lines through the 0.1 quantiles are presented.

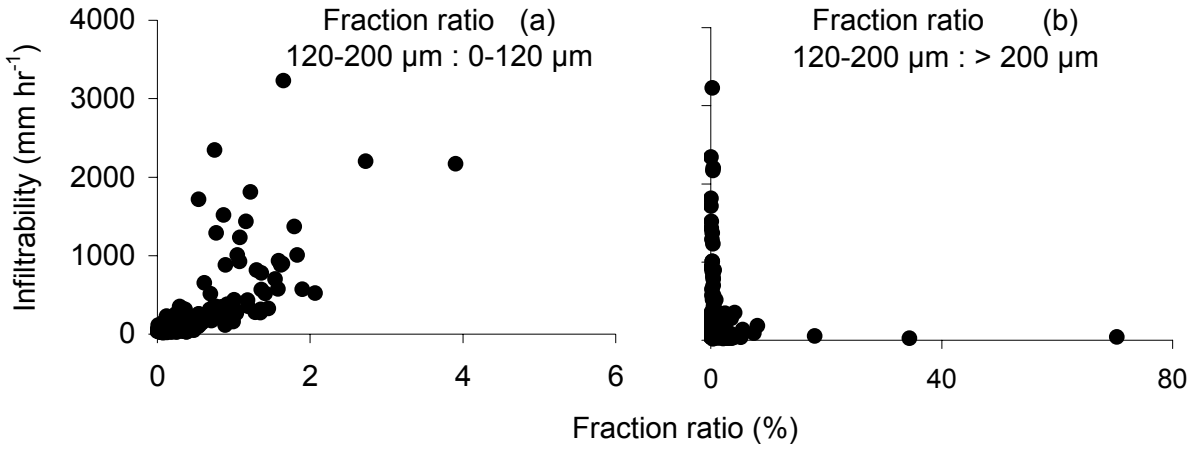


Figure 3.4. The relationships between soil infiltrability and a) the ratio of 120-200 µm to 0-120 µm fractions, and b) the ratio of 120-200 µm to > 200 µm fractions.

When the 120-200 µm fraction exceeded the < 120 µm fraction by 0.3 times, infiltrability was potentially maximal (Fig. 3.4a), and when the 120-200 µm fraction exceeded the > 200 µm fraction by 2 times, infiltrability was predictably minimal (Fig. 3.4b). The 0.1 quantiles of the 120-200 µm fraction increased when the content was above ~ 25 % (Fig. 3.5).

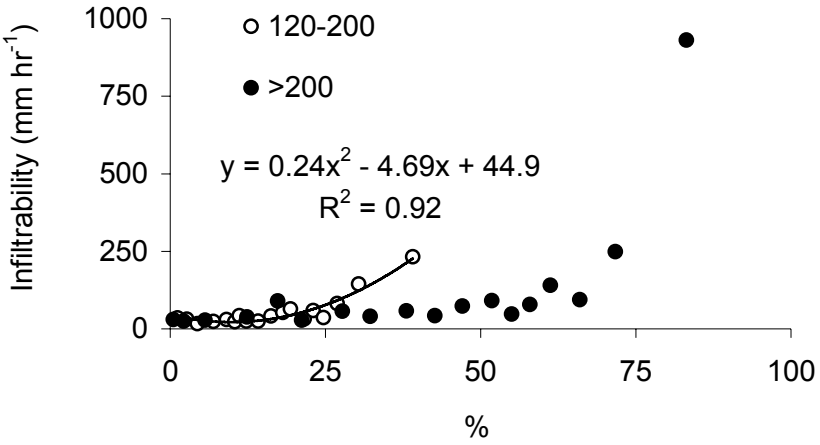


Figure 3.5. The relationships between soil infiltrability (0.1 quantiles) and the content of 120-200 µm and > 200 µm soil fractions.

The 200–250 µm fraction had a positive relationship with infiltrability. In soils with > 50 % in the > 200 µm size fraction (namely, fine, medium, coarse, and very coarse sand), infiltrability was potentially maximal (Fig. 3.2c). The 0.1 quantile of the > 200 µm fractions increased markedly when the content was above ~ 50 % (Fig. 3.5).

Figure 3.6 presents scatter plots for the relationships between infiltrability and clay and fine silt fractions determined by the three different techniques (the data is provided in Appendix B5). Mean clay and fine silt values were significantly different between all three techniques (Table 3.1, Student's t-test). Mean water-dispersible clay and fine silt content were significantly greater when determined by the laser analyser than by the pipette sampling (50 % greater for clay and 60 % for silt, $p < 0.01$). Total clay content determined by hydrometer was on average 43 % greater and total fine silt was 47 % less than the water-dispersible fractions determined by the laser technique.

Regression lines representing 0.95 quantiles showed better predictability (r^2) for the relationships between infiltrability and water-dispersible clay and fine silt content determined

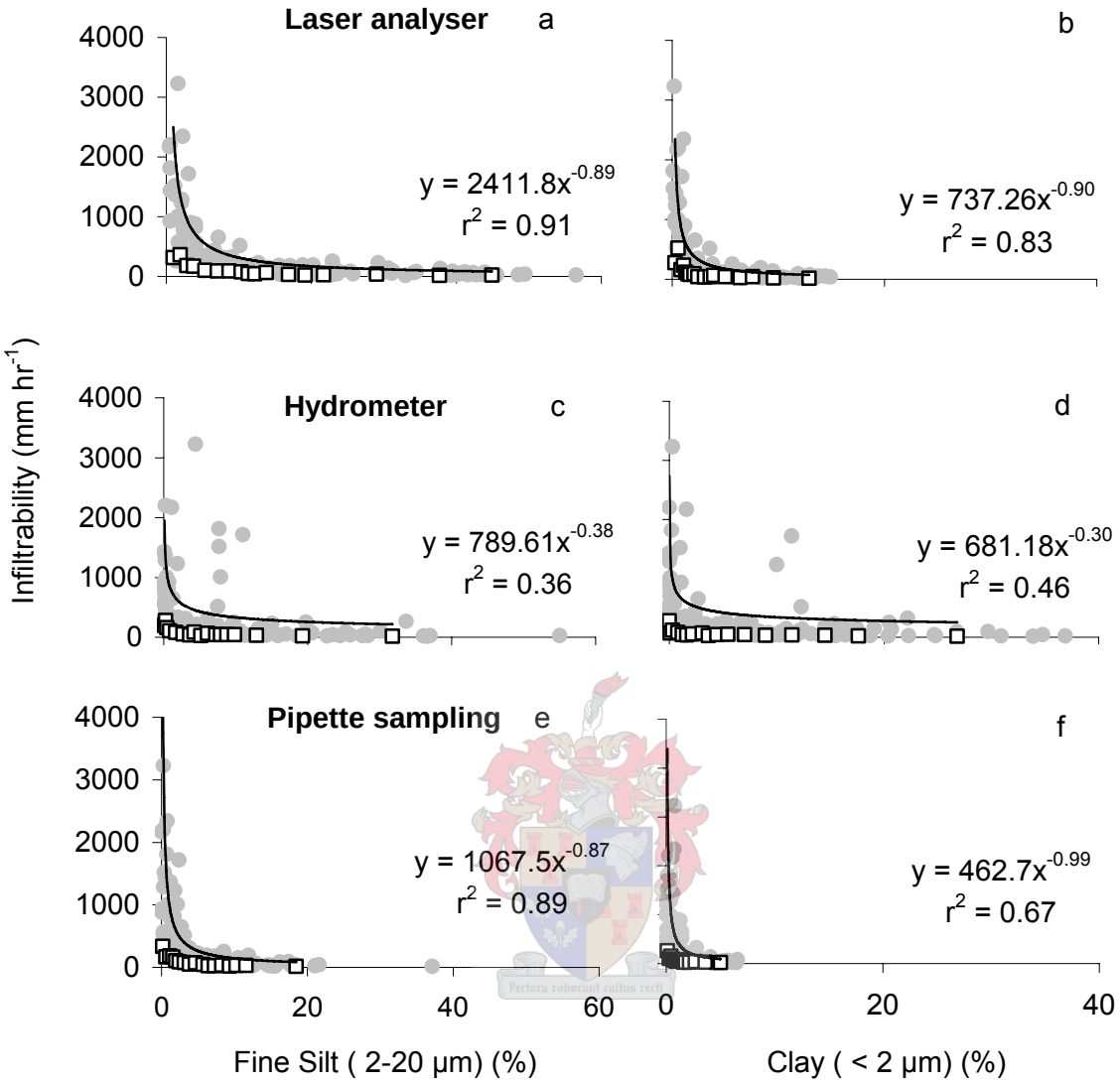


Figure 3.6. Relational envelopes derived from segmented quantile regression depicting the relationships between infiltrability and the content of soil fractions determined by three different techniques: a) fine silt (2-20 µm) by laser analyser; b) clay (< 2 µm) by laser analyser; c) fine silt (2-20 µm) by hydrometer; d) clay (< 2 µm) by hydrometer; e) fine silt (10-20 µm) by pipette sampling; and f) clay (< 2 µm) by pipette sampling. Open squares depict the 0.1 quantiles for 17 classes of each soil fraction. Within each class n = 10, except for the last class where n = 13. The formula and r^2 of the best-fit power regression lines fitted through the 0.95 quantiles are presented.

by the laser analyser than with total clay and fine silt determined by hydrometer (Fig. 3.6). Pearson correlation coefficients for the relationships between infiltrability and clay and fine silt content determined by the three techniques also showed that soil clay and fine silt content determined by the laser analyser had a better correlation than when determined by other techniques (Table 3.2).

Table 3.1. Mean values of clay and fine silt contents determined by laser analyser, hydrometer and pipette sampling.

Technique	Clay	Fine silt
Laser analyser		
Water-dispersed	4[a]	15[a]
Hydrometer		
Calgon-dispersed	7[b]	8[b]
Pipette sampling		
Water-dispersed	2	6

[a], [b] - different letters indicate significant differences between clay and fine silt values ($p < 0.01$) determined by different techniques.

Table 3.2. Pearson correlation coefficients for the relationships between soil infiltrability and clay and fine silt content determined by laser analyser, hydrometer and pipette sampling.

Technique	Soil fraction	Correlation coefficient
Laser analyser		
Water-dispersed	Clay	-0.43
	Fine silt	-0.47
Hydrometer		
Calgon-dispersed	Clay	-0.30
	Fine silt	-0.28
Pipette sampling		
Water-dispersed	Clay	-0.39
	Fine silt	-0.28

The results of the soil chemical analyses of 177 samples is presented in Table 3.3.

Table 3.3. Chemical properties of all 177 soil samples investigated in the present study. The data is presented as means and standard deviations.

	Exchangeable cations					ESP	EC[2]	pH[2]	OC[3]
	Ca	Mg	Na	K	CEC[1]	%	mS m^{-1}		%
			$mmol_c/kg$						
Mean	46	10	3	3	62	7	34	8	1
Standard Deviation	47	10	7	3	52	14	79	1	1

[1] - cation exchange capacity; [2] - 1:5 soil:water suspensions; [3] - organic carbon.

3.4 Discussion

The large sample size of this study allowed the use of a relational envelope approach to investigate relationships between soil infiltrability and particle size distribution. The advantage of this approach is that unlike correlation or regression analyses, ranges of potentially maximal and predictably reduced infiltrability can be detected. The boundary lines showed approximate threshold values (dotted line) for each fraction (Figs. 3.1 & 3.2), which subdivide the samples into ranges in which infiltrability is predictably minimal and ranges in which infiltrability is potentially maximal. The < 120 µm size fraction appeared to comprise a plasmic component of the soil crusts (Valentin and Bresson, 1992), i.e., a component which filled in pores and restricted infiltrability.

It is important to note that potentially minimal infiltrability values were greater in soils with a low content (i.e., < 2 %) of the < 70 µm fraction, than in soils with > 2 % of this fraction. This is evident by looking at the 0.1 quantile regression lines (Fig. 3.3), and suggests that these (< 70 µm) fractions may play an important role in crust formation and restriction of infiltrability. The 30-70 µm fractions appeared to play the most significant role in this regard, as at contents < 2 % of this fraction the potentially minimal infiltrability (i.e., the 0.1 quantile) was greater than at contents < 2 % of fractions < 30 µm.

High variability in infiltrability of samples with a plasmic fraction (i.e., < 120 µm) content below ~ 2 % (Fig. 3.1 & 3.2a) may relate to the effect of the other factors. Soil infiltrability

depends on numerous parameters apart from clay and silt content (Le Bissonnais, 2003). Clay mineralogy, for example, may greatly modify infiltrability. As shown by Mills et al. (2006b), soils with a clay fraction dominated by quartz particles had higher infiltrability than when the clay fraction was dominated by smectite and mica. This was attributed partly to the differences in shape and structure of these minerals. The angular shape of quartz particles may, for example, make them less prone to seal formation than oriented sheet-like structure of phyllosilicates.

The findings of the present study were in accordance with numerous studies which reported that silt (Lemos and Lutz, 1957; Kowal, 1972; Gabriels and Moldenhauer, 1978; DePloey and Mucher, 1981; Moss, 1991a & b; Moss and Watson, 1991) and clay fractions (McIntyre, 1958a & b; Tackett and Pearson, 1965; Evans and Buol, 1968; Morin et al., 1981) played a role in crust formation. The results, however, contradicted Moss (1991a), who reported that particles of < 10 μm, namely clay and fine silt, played no role in crust formation. Moss (1991a) investigated structural and erosion crusts in laboratory conditions in soils on a slope, and reported that particles of < 10 μm size were removed by air-splash and runoff flow. In field conditions, however, the washed off particles settle down in relief depositions, where they may form depositional crusts (Valentin and Bresson, 1992). In the present experiment, elements of both structural and depositional crusts were investigated given that the infiltration solution was kept within the syringe walls and there was no surface flow. If runoff had been restricted in Moss's (1991a) study, the dispersed fine particles may have filled the pores and restricted infiltrability. Differences between the findings of the present study and of Moss's (1991a) study may therefore be attributed to differences in the types of crust investigated, as different types of crusts have different structures (Valentin and Bresson, 1992).

An interesting finding was that soils with a high content of very fine sand (50-100 μm) had predictably minimal infiltrability (Fig. 3.1g & h). It is not widely recognized that very fine sand also plays a role in crust formation. Moss (1991a) reported that crust formation depended not only on the content of soil fraction per se, but on the mixture of different fractions, especially on the ratio of the (63-125 μm) fractions, namely very fine and fine sand, to the silt fraction (2-50 μm). The higher the ratio the greater was the infiltrability. Therefore, in Moss' (1991a) study the very fine and fine sand (63-125 μm) fraction seemed to play the so-called "skeletal" role, while the silt fraction played a plasmic role. By contrast, in the present study, both of these fractions appeared to play a plasmic role. This finding was in

accordance with Mills et al. (2006b), who reported that the very fine sand (50–106 µm) fraction restricted infiltrability. It is consequently possible that the very fine sand particles are fine enough to fill in the pores and may also be a part of plasmic component.

In the study presented here, equivocal relationships between infiltrability and the fine sand fraction (100-250 µm) were found. The 100-120 µm fraction behaved in a similar manner to the clay, silt and very fine sand fractions, and at levels above ~ 5 % restricted infiltrability (Fig. 3.2a). This fraction may therefore also be seen as a part of the plasmic component of crust.

Soil fractions of 120-200 µm did not show a clear relationship with infiltrability (Fig. 3.2b), possibly because it may play a plasmic or skeletal role in crust formation, depending on the prevalence of other size fractions that either promote blockage or promote pore formation. Figure 3.4 showed that the effect of the 120-200 µm fraction depended on its ratio to the < 120 µm fraction and to the > 200 µm fraction. When the 120-200 µm fraction was twice the coarse fraction (> 200 µm), infiltrability was predictably minimal, which suggested that in this case the 120-200 µm fraction played a plasmic role, filling in pores and restricting infiltrability. By contrast when the 120-200 µm fraction was more than one third of the unequivocally plasmic (< 120 µm) fraction, infiltrability was potentially maximal, which suggested that in this case the 120-200 µm fraction played a skeletal role (i.e., formed pores and promoted infiltrability). The 0.1 quantiles (Fig. 3.5) also showed that the 120-200 µm fraction may play a skeletal role, as at above ~ 25 % content of this fraction the minimal infiltrability values increased.

Fine, medium and coarse sand fractions (> 200 µm size) showed inverse patterns to those obtained for the relationships between clay, silt and very fine sand fractions (Fig. 3.2c). When the content of these fractions exceeded 50 %, infiltrability was potentially higher (which is evident from 0.95 [Fig. 3.2c] and 0.1 quantiles [Fig. 3.5]), suggesting that they formed the skeletal component of soil crusts. The explanation for greater infiltrability with a high skeletal component also lies in a concomitant decrease in finer particles (plasmic components).

High variability in infiltrability in samples with a > 200 µm fraction content exceeding 50 % indicates the possible influence of other factors modifying infiltrability (Fig. 3.2c). Some of the samples analysed in the sperent study had high ESP values (Table 3.3), which could

enchanced soil crusting process, as at high sodicity and low salinity conditions only a small amount of clay is required to block the pores (Felhendler et al., 1974; Pupisky and Shainberg 1979; Shainberg et al., 1981a; Shainberg and Letey, 1984), and reduce infiltrability.

The lower fine silt and clay content obtained with pipette sampling technique compared to the laser technique may be because in the laser technique, the 1:5 soil:water suspensions were constantly stirred in the water chamber in order to pass between parallel glass lenses where the laser beam was intercepted. This stirring could cause further dispersion of soils, and increase the clay and fine silt fractions in the soil samples. The better correlation found between infiltrability and soil fractions determined with laser than with pipette sampling may indicate better accuracy of the laser technique. It is a quick and automated technique, which makes it less sensitive to human error. Higher accuracy along with the possibility of determining smaller particle size fractions makes the laser technique a preferred method for investigating effects of particle size on infiltrability.

The experiments with the different particle size determination techniques showed that water-dispersible clay and silt provided greater insights into processes influencing infiltration than did total clay and silt content. This is evident from the higher Pearson correlation coefficients and higher r^2 values of the quantile regression lines, but is also evident by observing outlier values. There were considerably more outliers in the total clay and silt data (Fig. 3.6c & d) than in the water-dispersible data (Fig. 3.6a,b,e,f). These outlier points prove the rule: namely that a soil can have relatively high total clay and silt content, but that the infiltrability can be relatively high if the clay and silt are not dispersed. This finding is in accordance with Ben-Hur et al. (1985) who found relatively high infiltrability in soils with a high clay and silt content (> 20 %). These researchers explained that the high clay content added to the stability of soil aggregates, which in turn promoted infiltrability. The importance of clay in maintaining aggregate stability and promoting infiltrability was also acknowledged by Mamedov et al. (2001). By contrast, when aggregates break down and disperse under raindrop impact, only small amounts of dispersed clay are needed to clog the pores (Shainberg and Letey, 1984). Therefore, the findings of the present study showed once again the primary role of dispersion mechanisms in crust formation, as has been stated by numerous other researchers (McIntyre, 1958a & b; Agassi et al., 1981; Shainberg, 1985).

3.5 Conclusions

Relationships between narrow intervals of soil particle size fractions and infiltrability were established. Clay, fine silt, coarse silt, very fine sand, and fine sand fractions (< 120 μm) were found to play a significant role in crust formation. The results suggested that they comprised a plasmic component of soil crusts, i.e., filling in soil pores and restricting infiltrability. The application of relational envelope approach for the data analysis showed that at contents of these fractions in soils above ~ 5 %, infiltrability was predictably minimal, while below ~ 5 %, infiltrability varied being either high or low, depending on the other soil factors affecting crust formation. The fine sand fraction (120-200 μm) was found to play either a skeletal role (i.e., forming pores and thereby promoting infiltrability) or a plasmic role in crust formation. When the 120-200 μm fraction was double the coarse fraction (> 200 μm), infiltrability was restricted, which suggested that in this case the 120-200 μm fraction forms a plasmic component of soil crusts. By contrast, when the 120-200 μm fraction was more than one third of the plasmic fraction (i.e., < 120 μm), infiltrability was potentially maximal, which suggested that in this case the 120-200 μm fraction forms a skeletal component. Fine, medium and coarse sand fractions (> 200 μm) appeared to play a skeletal role in soil crusts. Infiltrability was potentially maximal when these fractions exceeded a threshold of 50 %, which is probably also related to a concomitant decrease of the plasmic crust-forming fraction. Infiltrability had a stronger correlation with water-dispersible than with total clay and fine silt content, which highlighted the importance of the dispersion mechanism in reduction of infiltrability.

CHAPTER 4: INFILTRABILITY AND CRUST FORMATION IN SOILS OF DIFFERENT TEXTURE, EC AND ESP

4.1 Introduction

One of the most important factors affecting soil infiltrability is the formation of crusts on the soil surface (Fox et al., 2004). Two main processes are recognized in crust formation: firstly physical breakdown of soil aggregates caused by the impact action of raindrops, and secondly chemical dispersion (Agassi et al., 1981; Kazman et al., 1983; Shainberg and Letey, 1984). Flocculation is yet another process, which may result in crust formation. Shainberg and Singer (1985) distinguished two types of soil crusts: a dispersion crust, formed as a result of aggregate breakdown due to raindrop impact and chemical dispersion; and a flocculation crust formed as a result of flocculation in soils with a high salinity dominated by polyvalent cations (Shainberg and Singer, 1985). Crusts formed with flocculated particles had greater permeability than crusts formed with dispersed particles.

The processes of dispersion versus flocculation are influenced by several soil characteristics, amongst which exchangeable sodium percentage (ESP) and the electrical conductivity (EC) of the soil solution are considered to be particularly important (Agassi et. al., 1981; Levy and Van der Watt, 1988; Eghbal et al., 1996; So, 2002; Le Bissonnais, 2003; Laker, 2004). A decrease in infiltrability at high ESP levels is frequently reported (Agassi et al., 1981; Kazman et al., 1983; Shainberg and Letey, 1984; Du Plessis and Shainberg, 1985; Miller and Gardiner, 1998; Robinson and Phillips, 2001). There is, however, no single common value, or threshold, at which ESP starts to promote soil dispersion across all soils (Laker, 2004). This threshold value for each soil is a function of other factors modifying the ESP effect. Electrical conductivity of the soil solution plays a major role in this regard (Agassi et al., 1981; Shainberg et al., 1981a; Kazman et al., 1983; Shainberg and Letey, 1984; Agassi et al., 1994; Hillel, 1998; Levy, 2000). As EC increases, the effect of ESP on soil dispersion is moderated (i.e., reduced in magnitude) (Oster and Schroer, 1979; Agassi et al., 1981; Shainberg et al., 1981a; Shainberg and Letey, 1984; Du Plessis and Shainberg, 1985).

The effect of ESP on dispersion is also modified by the presence of soil stabilizing agents such as sesquioxides and organic matter (McNeal et al., 1968; Du Plessis and Shainberg, 1985; Thompson, 1986), by clay mineralogy (Frenkel et al., 1978; Levy and Van der Watt,

1988; Stern et al., 1991; Levy et al., 1993; Laker, 2004) and by soil clay content (Shainberg and Letey, 1984; Ben-Hur et al., 1985).

Shainberg and Letey (1984) reported that in soils where clay swelling is the main mechanism affecting infiltrability, dispersibility of soils with high ESP levels increases with an increase in clay content. McNeal et al. (1968) and Frenkel et al. (1978) also reported that hydraulic conductivity (HC) reduction at high ESP levels increases with an increase in clay content. In fine-textured soils the small volume of conducting pores may be further reduced by swelling (Quirk and Schofield, 1955), which also results in a decrease in infiltrability (McNeal et al., 1966; Rowell et al., 1969). By contrast, in soils with low ESP, medium-textured soils were found to form crusts with slower HC than clayey soils (Ben-Hur et al., 1985). In the clayey soils, soil structure was more stable and crust formation was diminished. Interestingly, even soils with a coarse texture can be sensitive to high ESP and low EC (Shainberg and Letey, 1984). Pupisky and Shainberg (1979) obtained an 80 % reduction in the HC of sandy soils with a clay content of only 3.1 % when equilibrated with a solution with a SAR of 15, and leached with distilled water. In another study Felhendler et al. (1974) obtained complete sealing of a soil with a clay content of 10 % when equilibrated with a solution with a SAR of 10 (and also leached with distilled water). Shainberg and Letey (1984) explained that "unlike swelling, dispersion does not require a high clay content, as a small amount of dispersed clay is needed to clog the pores".

It is evident from the above that the effects of EC and ESP are likely to differ between soils of different particle size. The objective of the present study was to examine this hypothesis by studying infiltrability, dispersion and flocculation in soils of different texture, and determining the effect of EC and ESP on these processes.

4.2 Methods

4.2.1 Experimental analyses

Details of the study area and sample collection are given in Chapter 2. Samples were subjected to the following analyses: water-dispersible soil particle size distribution by laser technique (Saturn Digitizer 2500), total particle size distribution by pipette sampling (Day, 1965), extractable (Thomas, 1982) and soluble cations (Rhoades, 1982), EC (Rhoades, 1982), pH (Rhoades, 1982), organic carbon and total nitrogen (Eurovector Euro Elemental Analyser), and clay mineralogy (Day, 1965). More detailed information on these methods is

given in Appendix A. Based on the water-dispersible particle size results, 35 samples were selected and arranged into three textural groups: sand, loamy sand, silty loam. Samples within each group were further subdivided into subgroups according to their EC and ESP values. A summary of soil characteristics for the selected samples is presented in Table 4.1.

To minimize the effect of different factors modifying the main effect, comparisons were done on samples having similar characteristics. To investigate the effect of particle size on infiltrability, samples of similarly low EC & ESP (LL) values were compared within three particle size groups: sand, loamy sand, silty loam. To investigate the effect of EC and ESP, comparisons were done on samples of similar particle size. In the sand group, two subgroups with low ESP (LL) and high ESP (LH) values were compared. In the silty loam group, two subgroups with low EC & ESP (LL) and high EC & ESP (HH) were compared.

An index of crust formation was determined by measuring the infiltrability of soil by means of a rapid laboratory syringe method (Mills and Fey, 2004). The details regarding this method are given in Chapter 2. Infiltrability was measured at 30 second time intervals. To investigate the dispersion and flocculation processes, infiltrability was determined after adding different mobile phases into the soil columns. These mobile phases included dispersed soil and flocculated soil. Gypsum was used as a flocculating agent for preparation of the latter mobile phase, and a gypsum solution was also used as a control to investigate the effect of the flocculation of soil particles within the soil column. Distilled water was used as a baseline for comparison with the other three treatments. The treatments were consequently as follows:

- distilled water (W)
- gypsum solution (G)
- 1:5 soil suspension in gypsum solution (GS)
- 1:5 soil suspension in water (WS)

In the second treatment (G) a gypsum solution was prepared by dissolution of 10 g of gypsum in 1 L of water, and subsequent filtration through filter paper (Whatman no. 2). The EC of this solution was ~ 240 mS m^{-1}. In the third treatment (GS), a mobile phase was prepared by shaking 10 g of soil in 50 ml of gypsum solution. And in the fourth treatment (WS), a mobile phase was prepared by shaking 10 g of soil in 50 ml of distilled water.

Table 4.1. Physical and chemical characteristics of soil groups used in the present study.

Group	N	Clay+silt[1]	Exchangeable cations					ESP	EC[2]	pH[2]	OC[3]	TN[4]	Clay mineralogy				
		%	Ca	Mg	Na	K	Ca/Mg	%	mS m^{-1}		%	%	Qz	Mi	Kt	St	Fs
			mmol$_c$/kg										% of clay fraction				
Sand																	
Low EC & ESP (LL)	6	7	18	5	1	1	4	4	6	6	1	0.05	82^{a}	2^{a}	4^{a}	2^{a}	10^{a}
Low EC & high ESP (LH)	9	7	5	2	2	1	3	22	4	6	1	0.03	88^{a}	1^{a}	8^{ac}	0^{a}	2^{b}
Loamy sand																	
Low EC & ESP (LL)	9	18	27	6	1	2	4	3	7	7	1	0.05	40^{b}	21^{b}	15^{ab}	12^{b}	10^{a}
Silty loam																	
Low EC & ESP (LL)	6	75	50	20	3	5	2	4	21	8	1	0.08	37^{b}	34^{b}	11^{c}	7^{b}	6^{a}
High EC & ESP (HH)	5	73	27	39	27	5	1	23	282	7	1	0.09	9^{c}	38^{b}	39^{b}	6^{b}	0^{b}

$^{a, b, c}$ - indicate a significant difference ($p < 0.05$) between soil groups;
[1] - laser technique; [2] - 1:5 soil:water suspensions; [3] - organic carbon; [4] - total nitrogen.

4.2.2 Statistical analyses

To compare treatments repeated measures ANOVA (RMANOVA) analyses were performed. When a significant interaction was found between treatments a Bootstrap test was performed for comparing treatments at each time interval. The Bootstrap test is a multiple comparisons test, which confirms the Bonferonni Statistical test (Efron and Tibshirani, 1993), and which is used when values are not normally distributed. Changes in the infiltrability values over time intervals (from 30 to 300 seconds) were calculated. A Student's t-test was performed to compare: i) mean infiltrability values of samples having similar texture, but different EC & ESP values; ii) infiltrability values (0-300 second measurements) for different treatments in samples of high ESP values in the sand group; and iii) the quartz, mica, smectite, kaolinite and feldspar contents of clay fractions and exchangeable Ca/Mg content in different groups of samples. Statistica 7.0 (StatSoft 2004) was used for performing the ANOVA (RMANOVA) and Bootstrap analyses, and MSExcel for the Student's t-test.

4.3 Results

Significant differences in infiltrability ($p < 0.01$) were found between all three particle size groups. Infiltrability was highest in the sand group, followed by the loamy sand group, and then the silty loam group (Fig. 4.1). This pattern held regardless of the mobile phase used. Figure 4.2 shows the relationships between sum of soil clay and silt (clay + silt) content and infiltrability measured in four different mobile phases.

In the silty loam group no significant differences were evident between treatments, and infiltrability did not change significantly over time (Table 4.2, Fig. 4.3, Bootstrap test). In the loamy sand group, infiltrability decreased significantly (58 %, 30-300 seconds, $p < 0.05$,) in treatment WS (i.e., 1:5 soil suspension in water) (Table 4.2). Infiltrability in treatment WS was also significantly lower than in other treatments ($p < 0.05$) over the 0-300 second time interval (Fig. 4.3). In treatments W, GS and G, infiltrability did not change significantly over time, and there were no significant differences between them. In the sand group, infiltrability

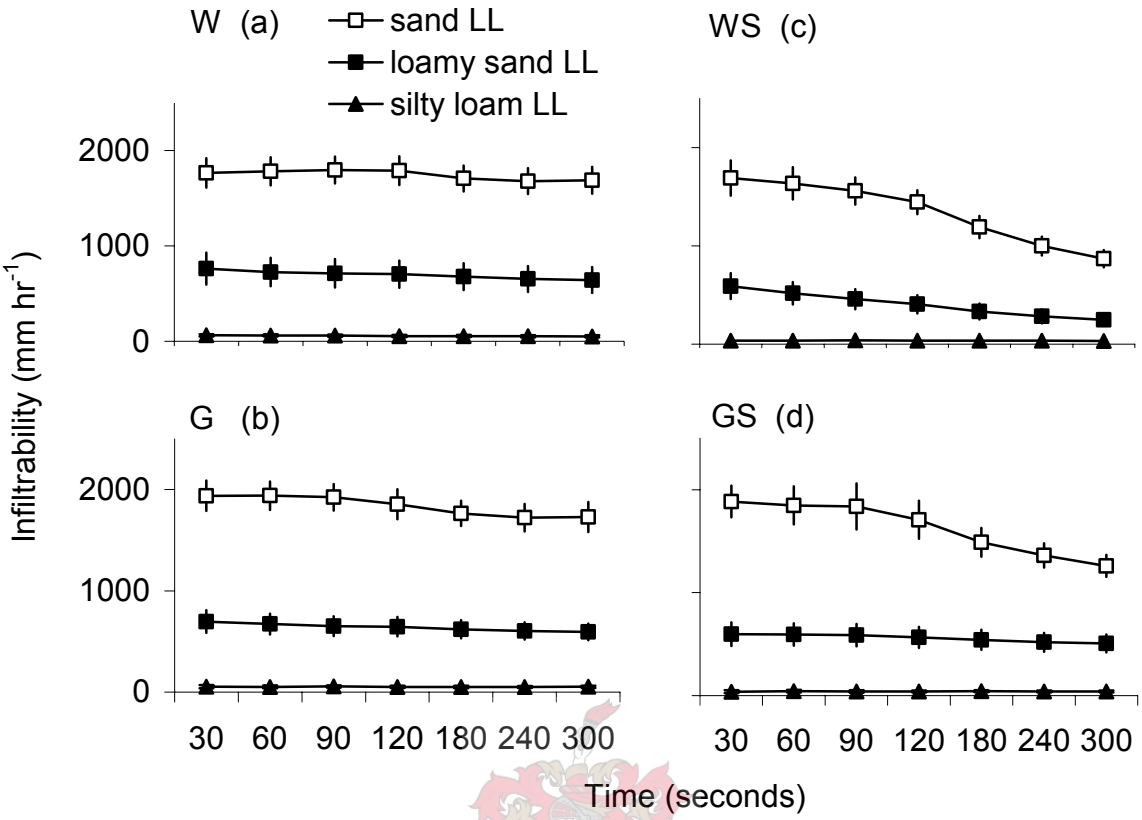


Figure 4.1. Soil infiltrability (mean and SE) in the LL (i.e., low EC & ESP) subgroup of the three particle size groups (i.e., sand, loamy sand and silty loam), measured in four different mobile phases: a) distilled water (W); b) gypsum solution (G); c) 1:5 soil suspension in water (WS); and d) 1:5 soil suspension in gypsum solution (GS).

decreased significantly (49 %, 30–300 seconds, $p < 0.05$) in treatment WS (i.e., 1:5 soil suspension in water) and (33 %, 30–300 seconds, $p < 0.05$) in treatment GS (i.e., 1:5 soil suspension in gypsum solution) (Table 4.2). Infiltrability in these two treatments was also significantly lower ($p < 0.05$) compared to the treatments W and G over the 0-300 second time interval. In the latter two treatments infiltrability did not change significantly over time (Fig. 4.3).

In the sand group, mean infiltrability was significantly greater ($p < 0.05$, Student's t-test) in samples of low ESP compared to samples of high ESP, regardless of the mobile phase used

(Figs. 4.4 & 4.5). Also in the sand group, samples with high ESP had significantly greater infiltrability ($p < 0.05$) in treatments W, G, and GS than in treatment WS over the 0-300 second time interval (Fig. 4.6). In the silty loam group infiltrability did not differ significantly between samples of low EC & ESP and high EC & ESP values.

The sand group had a significantly greater quartz ($p < 0.05$) and significantly lower mica and smectite content ($p < 0.05$) in the clay fraction than the loamy sand and silty loam groups (Table 4.1, Student's t-test).

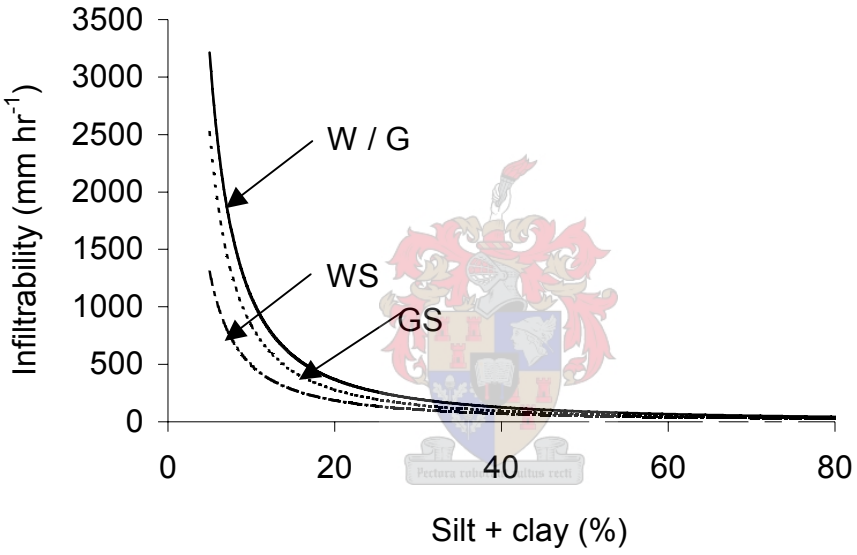


Figure 4.2. Relationships between infiltrability and water-dispersible clay + silt content in all 35 samples investigated, measured in four different mobile phases: distilled water (W); gypsum solution (G); 1:5 soil suspension in gypsum solution (GS); and 1:5 soil suspension in water (WS).

Table 4.2. Soil infiltrability measured at 30 and 300 second time intervals in the LL (low EC & ESP), LH (low EC & high ESP), and HH (high EC & ESP) subgroups of the three particle size groups (i.e., sand, loamy sand and silty loam), measured in four different mobile phases: distilled water (W); gypsum solution (G); 1:5 soil suspension in water (WS); and 1:5 soil suspension in gypsum solution (GS).

Group	Treatment	Infiltrability (mm hr^{-1})				Change in infiltrability over 30-300 s time intervals, %
		30 s*		300 s		
		Mean	SD	Mean	SD	
Sand (LL) (n=6)	W	1764	376	1687	346	4
	G	1938	367	1729	364	11
	WS	1689	440	869	216	49[a]
	GS	1885	378	1260	262	33[a]
Sand (LH) (n=9)	W	1511	590	1430	615	5
	G	1705	560	1498	573	12
	WS	1412	473	710	341	50[a]
	GS	1462	481	1138	416	22[a]
Loamy sand (LL) (n=9)	W	761	503	642	403	16
	G	696	336	595	246	15
	WS	590	397	248	189	58[a]
	GS	597	343	506	260	15
Silty loam (HH) (n=5)	W	51	38	45	35	12
	G	51	56	51	44	0
	WS	41	31	40	32	2
	GS	36	42	43	36	-19
Silty loam (LL) (n=6)	W	62	26	52	27	16
	G	55	39	53	27	4
	WS	35	24	34	14	3
	GS	38	35	40	25	-5

* - seconds;

[a] - indicates a significant difference ($p<0.05$) between infiltrability values measured at 30 and 300 second time intervals within the same group.

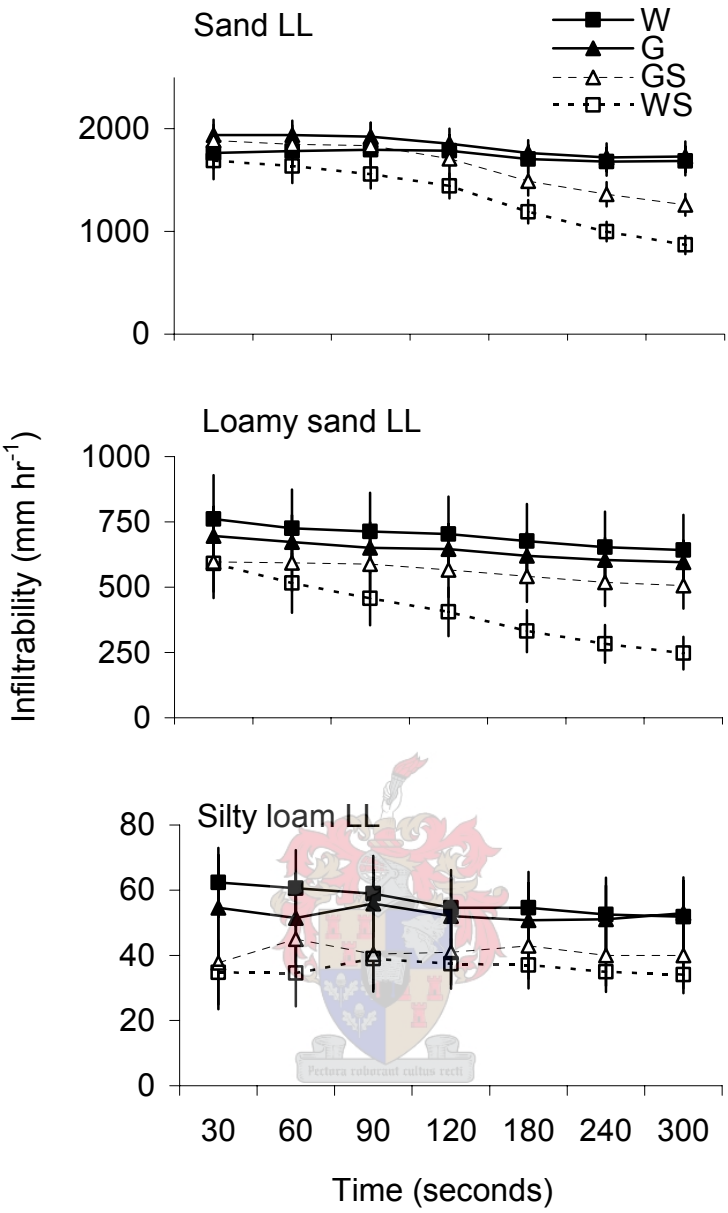


Figure 4.3. Soil infiltrability (mean and SE) in the LL (i.e., low EC & ESP) subgroup of the three particle size groups (i.e., sand, loamy sand and silty loam), measured in four different mobile phases: distilled water (W); gypsum solution (G); 1:5 soil suspension in gypsum solution (GS); and 1:5 soil suspension in water (WS).

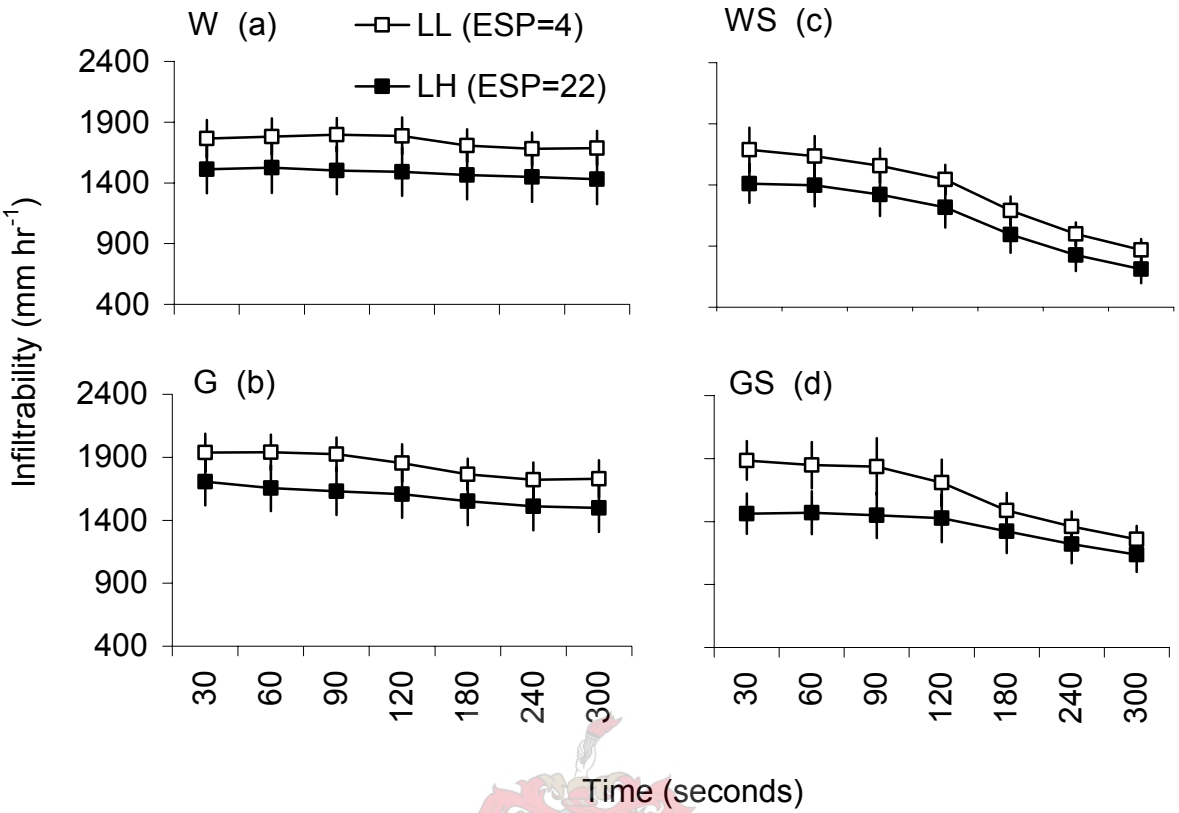


Figure 4.4. Soil infiltrability (mean and SE) in the LL (i.e., low EC & ESP) and LH (i.e., low EC & high ESP) subgroups of the sand group, measured in four different mobile phases: a) distilled water (W); b) gypsum solution (G); c) 1:5 soil suspension in water (WS); and d) 1:5 soil suspension in gypsum solution (GS).

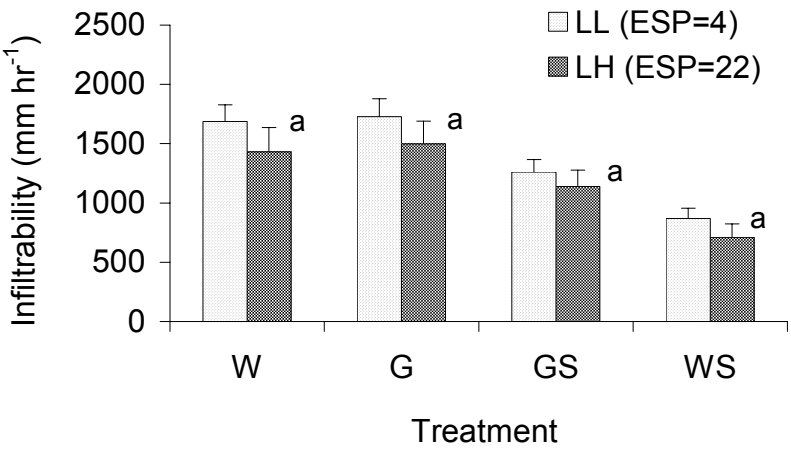


Figure 4.5. Soil infiltrability (mean and SE at 0-300 second time interval) in the LL (i.e., low EC & ESP) and LH (i.e., low EC & high ESP) subgroups of the sand group, measured in four different mobile phases: distilled water (W); gypsum solution (G); 1:5 soil suspension in gypsum solution (GS); and 1:5 soil suspension in water (WS). a - indicates a significant difference ($p < 0.05$) between LL and LH subgroups within treatments.

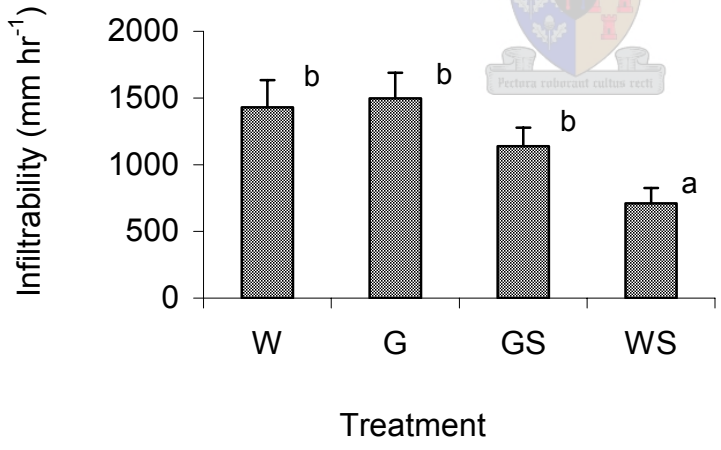


Figure 4.6. Soil infiltrability (mean and SE over 0-300 seconds) in the LH (i.e., low EC & high ESP) subgroup of the sand group, measured in four different mobile phases: distilled water (W); gypsum solution (G); 1:5 soil suspension in gypsum solution (GS); and 1:5 soil suspension in water (WS). a, b – different letters indicate a significant difference ($p < 0.05$) between treatments.

4.4 Discussion

The results of the present study showed that infiltrability increased with a decrease in clay content (Fig. 4.1). These findings were contradictory to Ben-Hur et al. (1985) who reported that medium-textured soils (~ 20 % clay) had a lower infiltration rate, than soils with relatively high clay content (~ 65 %). Ben-Hur et al. (1985) explained that as clay content increased, aggregate stability tended to increase, which in turn promoted infiltrability. A possible explanation for the different findings in the present study may lie in the effects of other factors modifying aggregate stability. These factors include clay mineralogy, organic matter, carbonates, sesquioxides and aluminum oxides, all of which act as stabilizing agents and at high levels may enhance aggregate stability (Singer and Le Bissonnais, 1998; Robinson and Phillips, 2001; So, 2002; Le Bissonnais, 2003). In addition, aggregate stability may depend on the composition of exchangeable cations. Calcium-dominated clays, for example, exhibit limited dispersion because in these soils the electrostatic attractive forces between the clay plates are greater than the repulsive pressures between the platelets (So, 2002). Ben-Hur et al. (1985) did not provide information regarding composition of exchangeable cations, however they investigated calcareous and typic rhodoxeralf soils which have free iron (Fe^{+3}). The presence of calcium carbonates and free iron may have enhanced aggregate stability. By contrast, in the present study most of the soils investigated were non-calcareous soils.

Exchangeable magnesium may also affect soil infiltrability. Magnesium-dominated clays have higher dispersibility than Ca-dominated clays (So, 2002). In addition, Mg displaces more Fe from the interlayer spaces of clays than Ca (Nel, 1989). This results in lower aggregate stability and deterioration in soil structure in soils with elevated exchangeable Mg levels (Levy, 2000). According to Sumner (1957) a low ratio of Ca/Mg may indicate greater erodibility of soils. In the present study, the Ca/Mg value in the silty loam group showed a trend of being lower than in sand and loamy sand groups, which may have made these soils more susceptible to crust formation (Table 4.1).

The pattern of lower infiltrability in silty loam soils held regardless of EC and ESP values (Fig. 4.2, Table 4.2). This contradicted Rapp's (1998) suggestion that ESP can totally override the effect of particle size distribution. In the silty loam group no significant effects of EC and ESP were observed. This is contrary to McNeal et al. (1968), Frenkel et al. (1978) and Shainberg and Letey (1984), all of whom reported that soils with a high clay content are more sensitive to changes in electrolyte concentration at high ESP than soils with a low clay

content. In the silty loam group of the present study the clay + silt content may have been so high that infiltrability was reduced by swelling and dispersion processes to the point where the effect of other factors such as ESP and EC was not noticeable. Shainberg and Letey (1984) reported that swelling in fine-textured soils is intense due to greater particle-to-particle contact points. In the present study swelling may have reduced the size of soil pores, thereby making these soils more susceptible to blockage through lodgement of dispersed particles. According to Shainberg and Letey (1984) and Levy (2000), in fine-textured soils clay probably moves only short distances before it plugs the pores. This may have resulted in almost immediate crust formation in the present study, compared to the sandy soils with larger pore sizes - in which macroscopic movement of dispersed particles takes place.

In contrast to the silty loam group, a significant effect of EC was found in the sand and loamy sand groups. In these groups, the treatment WS (i.e., 1:5 soil suspension in water) had a significantly lower infiltrability than other treatments (Fig. 4.3). This was in agreement with numerous other findings (Felhendler et al., 1974; Frenkel et al., 1978; Rowell and Shainberg, 1979; Pupisky and Shainberg, 1979; Shainberg et al., 1981a) and probably related to the dispersion process at low EC of the leaching solution. When the salt concentration is below a critical flocculation value, clay dispersion, movement, and lodging in the conducting pores is likely to be a key mechanism responsible for reduction of infiltrability (Shainberg and Letey, 1984).

Reduced infiltrability in the WS treatment over time in sandy soils may also relate to the high quartz content in the clay fraction (Table 4.1). According to Bühmann et al. (1996) and Laker (2004) the neutral charge and low Van der Waals' forces between clay-sized quartz particles makes soils with a high content of clay-sized quartz highly dispersible in distilled water.

The negative effect of the high ESP values on soil infiltrability found within the sand group (Figs. 4.4 & 4.5) was in accordance with numerous findings (Agassi et al., 1981; Kazman et al., 1983; Shainberg and Letey, 1984; Du Plessis and Shainberg, 1985; Miller and Gardiner, 1998; Robinson and Phillips, 2001). It is well known that high levels of ESP promote dispersion and crust formation of soils. According to Shainberg and Letey (1984), when clay dispersion is the main mechanism involved in crusting, only a small amount of dispersed clay is needed to clog the pores, therefore sandy soils (as investigated in the present study) can potentially be highly sensitive to high ESP when leached with distilled water.

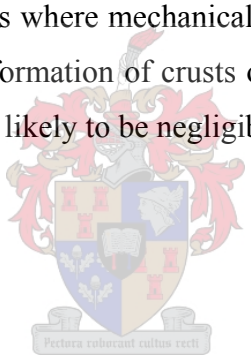
Application of gypsum enhanced infiltrability of soils with high ESP (Fig. 4.6). This finding was in agreement with previous studies (Shainberg et al., 1981a; Kazman et al., 1983; Miller, 1987). Gypsum has a flocculating effect because it increases the amount of divalent Ca^{2+} ions, and in turn decreases ESP. The higher ionic strength of the solution may have also increased the influence of Van der Waals' forces between particles leading to the formation of flocs (Goldberg et al., 2000). According to Shainberg and Singer (1985) flocculation can also play a role in crust formation; however, crusts formed with flocculated particles had faster permeability compared to crusts formed with dispersed particles. This may explain why infiltrability in the GS treatment was greater than the WS treatment, but still lower than in the W and G treatments (only water and gypsum-water solution).

An interesting finding was that the effect of gypsum was apparent only in treatments where crust formation took place (i.e., where a soil suspension was introduced into the syringe). Infiltrability was significantly greater in treatment GS (soil suspension in gypsum solution) than treatment WS (soil suspension in water) in both the sand and loamy sand groups. By contrast no significant differences were found between W and G treatments (where soil suspensions were not used) (Fig. 4.3). This suggests that the ameliorating effect of gypsum is only likely to take place in environments and soil, which are conducive to dispersion. In other words, without clay dispersion taking place, gypsum cannot ameliorate crusting.

Differences between treatments showed that the main mechanism restricting infiltrability is the formation of a crust (or seal) on the soil surface. In the W and G treatments, infiltrability did not decrease significantly and was probably governed by the particle size and pore size distribution within a soil column (Fig. 4.3). By contrast, in the treatments, where mechanical shaking of a soil suspension was involved, dispersion (WS treatment) and flocculation (GS treatment) of soil particles probably lead to the formation of a crust on the soil surface, which in turn significantly decreased infiltrability. This finding confirms the hypothesis that physical disruption of soil aggregates followed by chemical dispersion causes the crust formation on the soil surface and is the main mechanism reducing soil infiltrability on most soils under field conditions (McIntyre,1958a; Agassi et al., 1981; Shainberg, 1985; Moss, 1991a; Hillel, 1998; Fox et al., 2004).

4.5 Conclusions

The effects of soil texture, EC and ESP on infiltrability were determined. Soil dispersion and crust formation was found to be a main mechanism reducing infiltrability in the soil samples analyzed. Soil clay + silt content was the primary factor affecting infiltrability. In silty loam soils with 70 % of clay + silt, infiltrability was restricted to the point where EC and ESP did not play a significant role. The EC and ESP, however, significantly affected infiltrability of soils with low (7 %) and medium (18 %) clay + silt content. Sandy soils with high ESP had significantly lower infiltrability than soils with low ESP levels. The application of gypsum in these soils enhanced infiltrability of soils and minimized the negative effect of high ESP. This may be attributed to the increase in divalent Ca^{2+} ions, which in turn decreased ESP, and also to the increase of EC of the soil solution, which probably increased the attractive Van der Waals' forces between soil particles. As a result, dispersion of soil particles was minimized and soil infiltrability increased. The ameliorating effect of gypsum (relative to distilled water) was apparent only in those treatments where mechanical disturbance lead to desegregation of aggregates, clay dispersion and the formation of crusts on the soil surface. In non-dispersive environments the effect of gypsum is likely to be negligible.



CHAPTER 5: CONCLUSIONS

The present study had two main objectives: firstly, to investigate the relationships between plant species richness and soil properties with a particular focus on infiltrability; and secondly to enhance an understanding of the infiltrability mechanism in terms of the role of soil texture, electrical conductivity (EC) and exchangeable sodium percentage (ESP).

The study revealed interesting novel patterns in relationships between soil infiltrability, clay + silt, EC, pH and plant richness. The Grime's (1979) and Huston's (1979) theories proposed for the relationships between plant richness and soil nutrient availability were used to explained richness responses to investigated soil properties. It was suggested in the present investigation that soil conditions favourable for plant growth may enable high richness, because new species appearing as the result of speciation would have a relatively high rate of survival. By contrast, when conditions are unfavourable, a relatively few species will survive through time, i.e., the rate of attrition would be greater.

Of the soil properties investigated, infiltrability is of particular interest in semi-arid ecosystems, as it is one of the most important factors determining soil moisture. Despite the importance of infiltrability, to date it has not been comprehensively studied and a better understanding with respect to its effect on vegetation structure is required. The present study showed that infiltrability may play a significant role in determining plant richness. Ranges of infiltrability at which richness was potentially maximal differed between life forms. Phanerophytes and hemicryptophytes had potentially maximal richness at high infiltrability. By contrast, potentially maximal richness of chamaephytes and geophytes occurred at low infiltrability, and therophyte richness was potentially maximal at intermediate infiltrability. These different relationships for different life forms were in accordance with numerous findings (Minchin, 1989; Pausas, 1994; Austin et al., 1996; Gould and Walker, 1999), and were attributed to differences in the physiology of life forms. Each life form has a different requirement for moisture and has different adaptation strategies for accessing water. Phanerophytes with their long root systems can access water deep in the soil profile, and therefore, may be better adapted to the high infiltrability conditions. Although hemicryptophytes and therophytes absorb water from the upper layers of soils, in highly crusted areas accumulation of clay on soil surface can make extraction of water difficult. In addition, crusting may prevent germination and emergence of seedlings. Therefore low

infiltrability associated with crusting may restrict plant richness within the above life forms, as only few species may be adapted to survive these conditions. By contrast, chamaephytes and geophytes have adaptation strategies to survive long dry periods. Geophytes can store water in their underground organs, while chamaephytes have a relatively large root volume and a reduced osmotic potential, which promotes extraction of water in crusted areas (Olsvig-Whittaker et al., 1983). These adaptation strategies may through evolutionary time promote the survival of new species that arise through speciation processes.

The patterns observed for clay + silt content were opposite for that found for infiltrability. Richness of phanerophytes and hemicryptophytes was potentially maximal, and richness of chamaephytes and geophytes was predictably restricted at low clay + silt content. These contrasting patterns were attributed to the negative correlation found between infiltrability and clay + silt, high levels of which may promote crust formation and restrict infiltrability.

Different responses of the life forms to EC were attributed to differences in their tolerance to high salinity conditions. High salinity may reduce moisture availability through increasing osmotic pressure. This may be unfavourable for phanerophyte species, which require relatively large amounts of moisture. By contrast, chamaephytes and geophytes have better adaptation strategies to survive reduced moisture availability, and therefore they are unlikely to be as sensitive to high salinity conditions as phanerophytes. The present study found that chamaephytes and geophytes had potentially maximal richness at high EC. The physiological adaptation of chamaephytes and geophytes to high salinity requires further investigation.

An interesting finding was that richness of all life forms was restricted at pH > 9. This may relate to extreme nutrient deficiencies in alkaline soils, for example deficiencies of Zn, Mg, and Fe. Furthermore, high pH levels may increase dissolution of Al-organic complexes, which may result in Al toxicity to plants (McBride, 1994). These factors may restrict plant growth and result in only a few, highly specialized species surviving under such extreme conditions.

It should be noted that the relational envelope approach used in this study shows ranges along soil gradients, at which richness is only *potentially* maximal. This potentiality should be emphasized. This means that in terms of the investigated soil property, richness may be high, however, if some other controlling factor affects it, the richness can be restricted. This can be

seen in the example of geophyte richness, which was potentially maximal at low infiltrability. Low infiltrability is often associated with a relatively high pH, because of accumulation of sodium salts. The data showed, however, that at high pH richness of geophytes was restricted. Therefore at low infiltrability richness of geophytes may be restricted by high pH, and is only potentially maximal at both low infiltrability and intermediate pH.

The patterns observed in the present study may be a function of a single property investigated (e.g. soil infiltrability), but is more likely to be reflecting a complex interaction of all soil properties. Infiltrability is, for example, negatively correlated with clay + silt content, EC and pH. In fine-textured soils with high clay + silt content, soil crusting may restrict infiltrability, and in turn result in high salinity and pH conditions. In coarse-textured soils, by contrast, infiltrability and leaching is high, and salinity is usually low. This interrelationship makes it difficult to distinguish which soil property plays the controlling role. In addition, numerous other factors may affect plant richness, such as the interaction between species, vegetation architecture, and climatic conditions, all of which were not investigated in the present study. Therefore, causality cannot be demonstrated from the relational envelopes, but they do provide an enhanced understanding of ecological processes.

Due to the importance of infiltrability in plant ecosystems, further investigation was undertaken to enhance an understanding of factors influencing infiltrability. Soil texture has been defined as one of the main properties controlling infiltrability (Hillel, 1998; Miller and Gardiner, 1998; Shukla and Lal, 2002). There has, however, been no consensus in the literature with regards to which particle size fraction plays the most important role in crust formation. In order to enhance this understanding, relationships between infiltrability and small water-dispersible soil fractions were determined. The use of laser technology enabled the determination of smaller particle size fractions than is possible with conventional laboratory techniques.

Water-dispersible clay and fine silt fractions showed better correlation with infiltrability than total clay and silt content. This indicates that soil infiltrability was influenced more by the amount of the dispersed clay and fine silt particles than by the total content of these particles in soils. This highlighted once again the importance of the dispersion mechanism in reducing infiltrability, and suggests, that in soils having the same particle size distribution, infiltrability will be determined by the aggregate stability or the tendency of soils to disperse, which in

turn depends on stabilizing agents, such as organic carbon, sesquioxides and aluminum oxides.

In terms of particle size fractions, clay, fine and coarse silt, and very fine sand fractions (< 100 µm) appeared to play a plasmic role in soil crusts - filling in soil pores and restricting infiltrability. At contents of these fractions above 5 %, infiltrability was predictably minimal. This shows that these fractions act as a 'filter', playing a primary role in determining infiltrability if their content exceeds 5 %. The low content of these fractions does not, however, ensure high infiltrability. At the < 5 % of the < 100 µm fraction infiltrability varied, being either high or low, indicating that some other limiting factors are likely to be playing a primary role.

The relationship between infiltrability and the fine sand fraction (100-250 µm) was equivocal. The fraction in the 100-120 µm range showed a similar pattern to the clay, silt and very fine sand fractions, and at levels above 5 % restricted infiltrability. An interesting finding was that the 120-200 µm fraction could play both a plasmic and a skeletal (i.e., forming pores and promoting infiltrability) role, depending on its ratio to the < 120 µm fraction and to the > 200 µm fraction. When the ratio to the > 200 µm fraction exceeded two times, infiltrability was restricted. In this case the 120-200 µm fraction appeared to play a plasmic role. By contrast, when the 120-200 µm fraction exceeded the plasmic fraction (< 120 µm) by 0.3 times, infiltrability was potentially maximal, which indicated that in this case the 120-200 µm fraction played a skeletal role. Fine, medium and coarse sand fractions (> 200 µm) appeared to play a skeletal role in soil crusts. At high levels (i.e., > 50 %) of these skeletal fractions, infiltrability was potentially maximal. This could also be explained by the concomitant decrease of the plasmic fraction capable of reducing infiltrability by dispersing and clogging pores.

It has been previously reported that soil texture may modify the effect of the other two important properties determining infiltrability, namely EC and ESP (Shainberg and Letey, 1984; Ben-Hur et al., 1985). To investigate this, effects of EC and ESP on dispersion and flocculation were determined in soils of different texture. The results demonstrated that dispersion and formation of crusts on soil surface were the main mechanisms restricting infiltrability. Soil texture was found to play a primary role in crust formation in the investigated soils, with EC and ESP being of secondary importance. In soils having more than

70 % of clay + silt, infiltrability was restricted to the point where other properties, such as EC and ESP did not play a significant role. This contradicted Rapp's (1998) suggestion that ESP can totally override the effect of particle size. Clay + silt content in the present study was probably so high (> 70 %) that infiltrability values were reduced by swelling and dispersion processes to the point where the effect of other properties, such as ESP and EC, was unnoticeable. Swelling is more intense in fine-textured soils than in coarse-textured soils due to greater particle-to particle contact points (Shainberg and Letey, 1984) It may have reduced the size of soil pores, which made these soils more susceptible to blockage of infiltrability through lodgement of dispersed particles. This could have resulted in almost immediate crust formation, compared to the sandy soils with larger pore sizes, and macroscopic movement of dispersed particles.

Soil EC and ESP, however, significantly affected crust formation in sand and loamy sand soils with clay + silt contents below 18 %. In the sand group soils with high ESP had significantly lower infiltrability than soils with low ESP. The negative effect of high ESP values on infiltrability is widely recognized. In this study it in all likelihood increased the dispersion of soil particles and crust formation. Application of gypsum in sand and loamy sand soils increased infiltrability. This is probably because of i) a decrease in ESP due to an increase in Ca^{2+} concentration; and ii) an increase in EC. The higher EC of the soil solution could have increased the intensity of Van der Waals' forces between particles, thereby preventing dispersion and promoting the formation of flocs, which probably lead to the formation of crusts comprised of flocculated particles. According to Shainberg and Singer (1985) such crusts have faster permeability compared to crusts formed with dispersed particles. This may explain the higher infiltrability in the treatment with soil suspended in gypsum solution than in the treatment with soil suspended in distilled water. An interesting finding was that the effect of gypsum was apparent only in treatments where crust formation took place (i.e., in treatments with soil suspensions), suggesting that the ameliorating effect of gypsum is likely to take place only in soils conductive to dispersion.

In conclusion, the above findings enhanced an understanding of infiltrability mechanism in terms of the role of soil texture, EC and ESP. This may be extremely useful for successful conservation management in semi-arid areas. The results also demonstrated that soil properties, such as infiltrability, clay + silt, EC and pH may play an important role in determining plant richness. It would be instructive to investigate whether similar relationships

between richness of life forms and soil properties occur in other ecosystems at the scale of continents.

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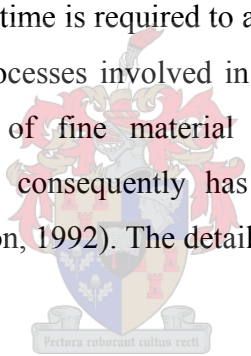
LIST OF APPENDICES

APPENDIX A: ANALYTICAL METHODS

A.1 Soil infiltrability through simulated crusts

A rapid laboratory method (Mills and Fey, 2004) was used for the estimation of infiltrability and the inherent crusting tendency of soils. This method involves the leaching of an agitated 1:5 soil : water suspension through a soil column (1.4 cm diameter). A slight modification of the published method was used, namely that soils were loosely packed rather than compacted. This was done to enable comparison of infiltrability across a wide range of soil types. According to Mills and Fey (2004) the results obtained with this method show a strong correlation with results obtained by using a laboratory rainfall simulation method, although infiltrability through the syringe is approximately 10 fold greater than under rainfall simulation. Infiltrability through the syringe is therefore not directly comparable with infiltrability in the field, but can provide an index of the inherent crusting tendency of the soil. A major advantage of the syringe method (compared to laboratory rainfall simulation) is that a relatively small amount of soil and time is required to assess the inherent crusting status of a soil. In this method all the main processes involved in crusting such as dispersion of clay, slaking of aggregates, deposition of fine material and mechanical energy input are accomplished. The simulated crust consequently has features of both depositional and structural crusts (Valentin and Bresson, 1992). The details of the method are presented below.



Procedure:

A 16 g of air-dried soil was agitated vigorously with 80 ml of distilled water in a 120 ml cylinder on a reciprocal shaker at 150 rpm for 5 minutes. Two replicas of each soil sample consisting of 5 g of soil packed into 10 ml plastic syringes were used. A 1 mm layer of cotton wool was placed at the base of the syringes before adding the dry soil. The syringes were then placed in distilled water to allow water to move up into the syringe and saturate the soil. The agitated soil suspension was left to settle for 5 minutes after which a 30 ml aliquot was carefully taken from the settled suspension using a pipette immersed to a depth of 15 cm to prevent disturbance of the settled sediment. For the investigation of the relationships between plant richness and infiltrability (Chapter 2) an aliquot of 7 ml was taken from a 30 ml bottle and pipetted gently into a syringe, while the base of the syringes was blocked by finger pressure to prevent premature drainage (Chapter 2). The syringes were then placed in a rack above a beaker on a digital balance and the bases of the syringes were released to allow

drainage into the beaker. The rate of water release from the syringes was recorded as the mass increase of the receiving beakers over time. For the investigation of the relationships between infiltrability and soil fractions (Chapter 3) and for the investigation of infiltrability in different particle size groups (Chapter 4), an aliquot of 7 ml of infiltrating solution was added into a syringe. After that the solution was kept at a 7 cm level by continuously adding the soil suspension using a pipette. This was done to maintain a constant hydraulic head, which was considered to be an improvement of the method, as the hydraulic head will affect infiltrability. The temperature in the laboratory may have fluctuated by a few degrees between measurements, but this effect was assumed to be negligible.

A.2 Water-dispersible clay and fine silt content by sedimentation and pipette sampling

Water-dispersible clay (< 2 μm) and fine silt (2-20 μm) were determined by sedimentation and pipette sampling (Soil Classification Working Group, 1991). This is a common laboratory procedure. The method was slightly modified to determine the dispersion of clay and silt which takes place during infiltrability measurements. For this purpose 50 g of soil was weighed into a beaker, after which 250 ml of distilled H_2O was added to make a 1:5 soil:water suspension. The beaker was then put onto a shaker for 5 min. The soil suspension was subsequently decanted into a 1 L glass cylinder and made up to 1 L with distilled water. The solution was thoroughly mixed with a rod for 1 minute and then left to stand to allow the dispersed particles to settle. The settling time depended on the temperature of the water suspensions and is shown in Table X. An aliquot of 25 ml was pipetted at the prescribed time from a 10 cm depth into a porcelain dish of recorded weight for fine silt + clay determination. The water was evaporated from the dish by placing it in a water bath. The porcelain dishes were finally put into an oven at 100ºC to ensure complete drying. The weight of sample was recorded. Another 25 ml aliquot was taken from the same cylinder for clay determination. It was taken from a 7 cm depth after the prescribed settling time shown in the Table A2.

Table A2. Settling times of fine silt and clay particle as a function of temperature.

Temperature	Fine Silt (0.02mm)		Clay (0.002mm)	
ºC	min	sec	hr	min
17	5	1	8	21
19	4	46	7	57
21	4	32	7	34

The fine silt and clay content were calculated using the following formulas:

Percent fine silt + clay (SC) = A x 1000 x 100 / E x 25,

Percent clay (C) = B x 1000 x 100 / E x 25,

Percent Fine Silt = SC – C,

Where:

A – mass(g) of pipetteted fine silt plus clay
B – mass(g) of pipetteted clay
E – mass of dry total soil sample

A.3 Calgon-dispersible clay and fine silt content determination by hydrometer

Calgon-dispersible clay (< 2 µm) and fine silt (2-20 µm) content were determined by hydrometer (Day, 1965) at the Institute of Soil Water and Climate, Pretoria.

Calibration of hydrometer:

The hydrometer was calibrated in the following manner: an aliquot of 100 ml of calgon solution was added to the sedimentation cylinder. The distilled water was added to calgon solution to make it up to 1 L. This was mixed thoroughly with the plunger, and brought up to the temperature of the sedimentation cabinet. The temperature was recorded. The hydrometer was lowered into the solution carefully, and scale of reading (Rl) was determined at the upper edge of the meniscus.

Procedure:

The 40 g of soil was weighted for determination of the oven-dry weight (Co) in an oven at 105ºC overnight. Another 40 g of soil was placed in a 600 ml beaker. A 100 ml of calgon solution and 400 ml of distilled water were also added to the beaker. The sample was left to

soak for 10 minutes. The suspension was then transferred into the dispersing cup. The suspension was mixed for 5 minutes with the motor mixer and transferred to the sedimentation cylinder. The level was brought up to the 1000 ml mark with distilled water. The cylinder was then moved into the sedimentation cabinet. The temperature of the suspension was recorded. When the temperature became constant the plunger was inserted and moved up and down to achieve mixing of the contents. The plunger was then removed and time was recorded. After 30 seconds the hydrometer was carefully inserted into the suspension after and reading (R) was taken. Without removing the hydrometer, the reading was taken again after 1 minute. After this the hydrometer was carefully removed, rinsed and wiped with a soft towel. Without remixing the suspension between measurements, readings were taken at 3, 10, 30, 90, 270 and 720 minutes. The concentration of suspensions was calculated for each reading according to the formula:

$C = R - Rl$

The summation percentage was then calculated with equation:

$P = 100 (C / Co),$

Where Co (g/L) is the oven-dry weight of soil.

The corresponding particle sizes or ‘diameters’ were then calculated by the equation:

$X (microns) = \theta / (t)^{1/2}$

Where t is the sedimentation time in minutes, and θ is a sedimentation parameter obtained from Table A3.

The P values were plotted versus X values on semilogarithmic paper. The summation percentages were then interpolated for particular X values: 2, 20, 50, 106, and 250 µm.

Table A3. Values of for determination of particle size from observed hydrometer readings (Day, 1965).

R	θ
1	48.9
5	47.9
10	46.7
15	45.3
20	43.9
25	42.5
30	41.0
35	39.5
40	38.0

A.4 Water-dispersible particle size determination by laser technique

A High Definition Digital Particle Size Analyzer, Saturn Digitizer 5200 machine coupled with computer (Pentium IV) was used for the determination of soil particle size fractions. The Saturn Digitiser 5200 uses a laser in conjunction with a charge-coupled device, containing over one million detector elements to measure particle size. These detectors are placed so that they can measure the intensity of light scattered by the particles at various angles. Light is scattered by the particles in a pattern dependent on their size, shape, refractive index, and wavelength of incident light. The particle size distribution is calculated from the angle distribution of the scattered light intensity collected by the detectors. The advantage of the laser technique compared to the laboratory technique is that it is a faster procedure, is more precise and it allows determination of smaller intervals of soil particle size fractions (Levy et al., 1993). Particles can be analyzed and measured over a range of 0.1 to 1000 μm. The particle size fractions were determined at the following intervals (given in μm): < 2, 2-5 , 5-10 , 10-20 , 20-30, 30-40, 40-50, 50-70, 70-100, 100-120, 120-140, 140-165, 165-185, 185-200, 200-230, 230-275, 275-310, 310-350, 350-410, 410-500, > 500. The analyses were done at the Department of Process Engineering, Stellenbosch University.

Samples in a 1:5 soil:water ratio were shaken on a reciprocal shaker for 5 min prior to the analyses. The suspensions were subsequently transferred into a machine chamber filled with distilled water. The sample was then pumped continuously from a chamber between parallel glass lenses, which intercepted the laser beam.

A.5 pH

Soil pH was determined in 1:5 soil:water suspensions (Rhoades, 1982). Mixtures composed of 10 g of soil and 50 ml of distilled water were shaken for 1 hr on a reciprocating shaker. The readings were taken with a pH meter (Metrohm 744, Swisslab, Germany), calibrated with standard buffer solutions.

A.6 Electrical conductivity

The tendency of an aqueous solution to conduct an electric current is correlated to the presence of ions in solution, and, therefore, is often used as an indication of salinity or total dissolved solids.

Electrical conductivity was determined in 1:5 soil:water suspensions (Rhoades, 1982). Analyses were done by mixing 10 g of soil with 50 ml of distilled water and shaking this mixture for 1 hr on a reciprocal shaker. The readings were then taken with an EC meter (Jenway 4510, Adcock Ingram, Switzerland).

A.7 Soluble cations

The concentrations of water-soluble cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were determined using Atomic Absorption Spectrometry (Rhoades, 1982). In the Atomic Absorption Spectrometry technique liquid samples are aspirated into a flame and atomised. Ground state atoms absorb energy in the form of light of a specific wavelength and are elevated to an excited state. The amount of light energy absorbed at this wavelength increases as the number of atoms of the selected element in the light path increases. The concentration of an element in the original sample can be determined by relating the amount of light absorbed to that of the element in a standard of known concentration.

A mixture consisting of 10 g of soil (< 2 mm) and 50ml of distilled water were shaken for 1 hour on a reciprocal shaker at 350 rpm. The suspensions were then filtered through Whatman No.2 filter paper and subjected to Atomic Absorption Spectrometry using FS Varian 240 machine (Smminstruments, Australia) at the Department of Soil Science, Stellenbosch University.

A.8 Extractable cations

The concentration of ammonium acetate-extractable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were determined using Atomic Absorption Spectrometry (Thomas, 1982). Soil suspensions, containing 5 g of soil and 50 ml of 1M pH7 Ammonium Accetate solution each were shaken horizontally on a reciprocal shaker for 30 min at 350 rpm. The suspensions were then filtered through Whatman No.2 filter paper. The filtered extracts were subjected to Atomic Absorption Spectrometry, using FS Varian 240 machine (Smminstruments, Australia) at the Soil Science Department, University of Stellenbosch.

A.9 Exchangeable cations

Exchangeable cation concentrations were determined by subtraction of soluble cations concentrations from extractable cations concentrations. The exchangeable sodium percentage (ESP) was calculated from exchangeable cation concentrations as follows:

$$ESP = Na^{+} / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})$$

A.10 Total carbon and nitrogen

Total carbon and nitrogen content in soils were determined using a EuroVector Euro Elemental Analyzer (Wirsam Scientific, Italy) coupled with a computer Pentium IV, at the Department of Soil Science, Stellenbosch University. This instrument uses a chromatographic technique and is capable of simultaneous determination of carbon and nitrogen.

Procedure:

Careful sample preparation and grinding of the soil was done to insure that a representative sample was analyzed. Samples were finely ground in a stainless steel ball mill before analyses. Soil samples (5-10 mg) were then carefully placed into tin sample cups using a spatula. The weight was recorded to the nearest 0.1 mg. The sample cups were then crimped to confine them, and placed into a quartz reactor. The quartz reactor was maintained at 1050ºC with a constant flow of He gas. Flash combustion occurred when a pulse of O_2 was injected into the quartz reactor shortly after introduction of the sample. Under high temperature conditions and in a presence of O_2, the tin was oxidized to SnO_2 resulting in a further temperature increase to 1700-1800ºC and the complete combustion of the soil organic matter. The combustion products (CO_2, nitrogen oxides, and water vapour) were swept by the helium carrier gas through a column filled with a chromium dioxide (CrO_2) in order to

catalyze oxidation of organic fragments and silver coated Co_3O_4 in order to remove halogens and sulphur oxides. The gases then passed through a heated Cu (650ºC) column to remove excess oxygen, a $Mg(ClO_4)_2$ column to remove H_2O and a chromatographic column for separation of N_2 and CO_2 gases. The different gases were detected with a thermal conductivity detector.

A.11 Inorganic carbon

Inorganic carbon was determined by quantitative determination of calcium carbonate using gravimetric analysis (US Salinity Laboratory Staff, 1954). The method is based on the reaction of HCl with calcium carbonate and the gravimetric loss of CO_2 from a sample. The method detection limit is approximately 0.2 % $CaCO_3$ equivalent and is generally reproducible within a range of 10 % of the final value.

Procedure:

A10 ml volume of 3M HCl was added into a plastic bottle and the weight of HCl, bottle, snap-lid was recorded to the nearest 0.1 mg. A mass of 2-5 g of air-dried (< 2 mm) soil sample was then placed into the bottle. The weight of soil transferred was also accurately recorded to the nearest 0.1 mg before adding it into the bottle. Three standards ranging from 100 to 300 mg of calcium carbonate were prepared. After the effervescence had subsided the snap-lid was replaced and the sample was placed onto a shaker for 15 min. The sample was left to stand for 2 hours. The vial snap-lids were large enough to permit gas exchange of CO_2, yet small enough to minimize loss of water vapor. Three distilled water blanks were included in the analysis to determine water vapor loss. After 2 hours, bottles weights were recorded to the nearest 0.1 mg. Blanks weight loss was subtracted to compensate for water vapour loss. Recovery of the calcium carbonate standards was verified. Calcium carbonate concentration in samples was calculated according to the following formula:

CO_3-C, % = (g CO_2 lost) x 0.2727 x 100 / g-air dry soil

$CaCO_3$-C, % = (g CO_2 lost) x 2.273 x 100 / g air-dry soil (to check standards)

Organic carbon content was calculated by subtracting the inorganic carbon value from the total carbon value.

A.12 Mineralogy of clay fraction

The mineralogy of the clay fraction of each sample was determined by using a Philips X-ray diffractometer and graphite-monochromated Co-Kα radiation, generated at 40 mA and 45 kV. Analyses were conducted by the Institute of Soil Water and Climate, Pretoria. Samples were dispersed ultrasonically and the clay (< 2 μm) fraction was separated by centrifugation. This fraction was then saturated with Mg and K by shaking in a 1 Mol dm^{-3} chloride solution for 1 hour and left to equilibrate overnight. The flocculated clay was freed of excess salt by repeated centrifuge washings. Orientation of the clay was achieved by the suction method on a ceramic plate. Expansion tests were performed by salvation with ethylene glycol and glycerol vapour at 60ºC and 90ºC, respectively (Novich and Martin, 1983). K-saturated samples were heated at 110 and 550ºC. Clay slides were scanned from 2 to 35 º 2θ. Semi-quantitative estimates were based on peak height percentages. Clay mineral nomenclature followed AIPEA recommendations (Bailey, 1980).

APPENDIX B: ANALYTICAL RESULTS

Appendix B1: Soil infiltrability, water-dispersible silt + clay, EC, pH and species richness of life forms at investigated plots.

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
1	K02	37	12.2	106	9.6	5	0	2	7	0
2	K07	51	5.4	81	9.5	5	2	3	14	1
3	K20	38	8.5	82	9.4	3	2	2	4	1
4	K22	63	7.5	109	9.7	5	0	2	11	3
5	K26	45	7.1	77	9.6	5	4	2	8	0
6	K34	63	3.4	52	9.6	6	1	0	16	3
7	K42	44	9.5	84	9.6	3	0	3	8	0
8	K46	37	6.1	87	9.5	4	0	2	8	2
9	K49	35	5.5	85	9.4	1	0	1	6	2
10	K50	36	6.9	92	9.6	6	0	3	5	0
11	K59	22	10.2	108	9.7	3	2	2	6	2
12	K62	40	5.0	80	9.3	3	0	0	5	0
13	K80	52	5.1	58	9.2	7	1	1	5	0
14	K85	61	7.5	83	9.5	2	2	1	10	4
15	K86	41	7.7	84	9.5	4	2	1	4	3
16	K88	34	11.0	109	9.6	1	1	2	8	1
17	K90	36	5.7	88	9.7	7	1	3	13	2
18	K91	41	6.9	44	9.1	6	0	0	12	2
19	N08	36	11.4	181	9.1	16	3	7	3	0
20	N09	35	11.1	106	9.2	28	0	12	13	1
21	N28	66	11.4	117	8.6	30	3	3	6	2
22	N36	66	10.9	117	9.3	11	1	3	4	0
23	N47	87	10.8	135	9.2	7	1	3	10	3
24	N66	100	10.9	152	9.5	2	3	0	3	0
25	N67	72	10.9	189	9.8	2	1	0	4	0
26	N72	43	11.0	92	9.4	4	1	0	6	2
27	N81AJM	34	8.0	194	10.5	7	1	1	11	3
28	N84	35	6.9	83	9.7	6	0	2	6	1
29	N87	81	9.2	123	9.6	2	1	1	3	1
30	N98	34	13.6	148	9.8	0	1	0	3	0
31	N99	46	9.0	84	9.5	2	1	1	9	2
32	Y03	97	2.3	186	9.6	7	0	5	3	0
33	Y09	154	1.8	126	9.5	7	0	4	4	0
34	Y21	214	1.4	88	9.9	10	0	2	6	0
35	Y22	306	1.2	114	9.7	6	0	2	4	0
36	Y23	195	2.2	193	9.6	7	0	3	2	0
37	Y25	201	0.9	245	9.9	9	0	3	4	2
38	Y26	287	1.2	108	9.7	7	0	4	4	0
39	Y30	234	0.7	153	9.9	7	0	2	5	0
40	Y39	171	1.1	135	10.0	11	0	5	4	0
41	Y52	430	1.2	151	9.6	10	0	2	4	1
42	Y61	158	2.6	282	9.8	10	0	4	2	1
43	Y62	359	1.0	166	9.8	10	1	3	5	1
44	Y67	127	1.7	143	9.7	5	0	2	3	0
45	Y72	320	0.8	152	9.6	10	0	3	4	0

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
46	Y74	453	0.3	184	9.9	11	0	2	5	4
47	Y76	482	0.7	134	10.0	3	0	0	3	2
48	Y84	1072	1.1	103	9.6	13	0	4	5	4
49	Y92	526	1.2	189	10.0	10	0	2	3	0
50	Y98	129	1.2	159	9.8	13	0	4	5	1
51	Y99	242	1.4	229	9.6	9	0	3	5	0
52	SN06	105	1.7	97	7.5	13	3	3	13	3
53	SN11	138	8.4	200	6.3	19	6	2	20	2
54	SN16	154	8.2	605	6.4	16	3	4	22	1
55	SN19	117	7.3	50	7.2	9	4	1	18	2
56	SN25	113	3.5	285	6.7	16	2	4	19	2
57	SN41	168	3.6	262	6.5	19	3	8	20	4
58	SN51	139	6.2	99	7.1	22	5	7	18	3
59	SN55	125	7.3	154	8.5	16	2	4	19	0
60	SN62	122	4.2	226	7.7	22	6	4	18	2
61	SN70	94	3.0	368	6.6	16	3	4	24	3
62	SN74	92	3.5	152	7.2	19	4	5	21	1
63	SN75	109	3.8	168	6.8	14	3	6	17	3
64	SN80	66	10.7	267	6.6	15	2	2	16	1
65	SN84	74	9.6	163	8.5	7	2	3	14	2
66	SN86	222	7.9	189	7.2	16	3	4	18	2
67	SN92	81	5.0	222	7.4	6	3	4	22	1
68	SN97	94	6.7	242	7.6	11	3	1	19	1
69	SN98	151	6.2	117	7.8	11	5	3	27	3
70	SN99	98	9.3	346	6.6	22	7	1	9	2
71	PK01	48	5.0	48	6.9	23	15	6	18	4
72	PK04	82	3.5	46	6.1	13	2	1	3	2
73	PK10	85	3.6	32	7.2	25	16	3	17	1
74	PK12	99	4.4	121	7.4	32	9	7	14	3
75	PK23	74	4.7	33	7.4	31	8	3	15	1
76	PK24	43	4.5	41	7.3	14	10	2	18	1
77	PK27	97	4.6	144	7.0	12	7	0	15	0
78	PK30	77	3.8	40	7.3	25	16	2	14	3
79	PK37	55	5.6	42	6.1	21	2	1	7	1
80	PK44	139	3.4	44	7.1	25	3	6	3	3
81	PK54	63	3.8	34	7.2	20	9	3	13	0
82	PK61	78	4.5	102	7.2	12	6	2	16	1
83	PK62	176	4.6	5620	8.3	16	1	1	26	5
84	PK80	138	4.1	1469	8.1	3	3	2	8	0
85	PK81	70	3.6	43	7.5	22	13	2	16	3
86	PK87	65	5.0	82	6.5	31	15	4	15	4
87	PK91	77	4.8	331	8.2	3	1	3	12	0
88	PK94	121	3.7	33	7.8	23	18	5	19	3
89	PK96	47	3.4	39	7.8	34	17	2	24	3
90	RH06	81	8.7	27	7.5	36	13	4	11	4

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
91	RH07	45	8.6	34	7.4	26	13	2	9	2
92	RH11	97	7.5	106	8.3	14	9	3	10	0
93	RH15	110	5.9	39	7.6	21	7	3	7	1
94	RH22	435	3.2	23	7.2	8	3	2	12	1
95	RH23	102	3.3	119	8.4	14	9	5	27	13
96	RH24	132	4.9	42	7.5	37	8	3	7	1
97	RH30	24	8.4	28	6.8	26	13	3	9	2
98	RH34	122	4.8	22	7.0	28	0	2	9	10
99	RH40	164	5.9	36	5.6	15	0	1	13	8
100	RH42	225	3.9	50	5.5	29	10	3	10	3
101	RH45	101	3.2	45	7.3	22	8	4	13	1
102	RH46	263	2.6	58	7.3	16	2	2	13	1
103	RH64	132	8.0	78	6.5	16	1	4	6	2
104	RH65	74	10.6	119	8.3	15	6	3	14	0
105	RH72	82	5.6	45	6.1	30	11	7	10	6
106	RH74	82	6.3	27	6.3	21	9	2	8	3
107	RH87	83	7.5	64	6.4	26	11	4	5	3
108	RH88	85	5.5	38	6.0	9	2	4	7	1
109	RH96	86	7.4	62	5.8	16	3	1	4	2
110	GH03	15	19.0	1772	7.0	13	4	0	3	0
111	GH06	62	13.8	1519	6.5	21	1	0	3	0
112	GH09	48	8.6	65	8.4	17	1	1	8	0
113	GH12	37	16.1	901	6.7	16	1	2	2	0
114	GH13	21	25.7	525	4.7	30	2	2	0	0
115	GH20	21	3.9	3710	8.1	11	1	0	3	0
116	GH25	38	10.2	439	8.5	19	5	2	6	0
117	GH33	31	11.8	885	7.4	21	3	2	1	0
118	GH38	29	10.2	2510	7.5	12	0	0	6	0
119	GH45	98	10.0	1188	8.0	18	2	2	8	0
120	GH61	100	11.2	2350	6.5	7	0	1	2	0
121	GH68	113	9.1	180	9.1	14	3	5	25	1
122	GH69	81	22.3	2810	8.8	9	1	3	6	0
123	GH76	30	27.6	443	9.2	18	2	2	9	0
124	GH80	55	20.5	427	7.0	38	10	1	6	0
125	GH83	37	20.6	1257	6.9	16	1	0	0	0
126	GH94	30	34.0	326	9.3	20	0	2	1	0
127	RG00	10	15.2	195	8.0	13	4	1	9	0
128	RG03	10	14.9	1269	5.4	30	10	1	9	1
129	RG28	22	10.4	1265	6.8	15	1	5	1	0
130	RG38	38	11.0	606	5.5	18	6	2	3	1
131	RG39	33	9.0	2620	6.5	15	7	2	8	0
132	RG47	23	10.0	399	5.0	12	0	4	1	0
133	RG49	26	10.0	1160	6.7	19	0	7	1	0
134	RG57	99	3.5	319	7.2	24	1	2	7	0
135	RG60	9	12.4	245	7.7	19	6	3	9	0

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
136	RG63	14	9.6	167	7.6	22	0	1	3	0
137	RG68	69	5.0	164	8.7	18	2	1	6	0
138	RG73	50	7.5	1065	7.7	20	4	2	5	0
139	RG78	90	3.9	477	8.2	19	0	2	8	0
140	RG80	32	11.3	250	8.6	16	0	3	5	0
141	RG81	86	6.9	218	8.9	27	5	5	22	1
142	RG94	31	13.0	585	5.0	20	0	2	2	0
143	RG96	152	4.3	273	7.1	22	0	2	3	0
144	MD02	36	20.3	3290	8.7	20	4	3	19	2
145	MD07	143	6.9	5530	7.8	9	1	0	3	0
146	MD17	230	6.6	5620	8.0	22	1	0	10	0
147	MD23	253	14.4	3850	8.7	28	3	2	8	0
148	MD26	169	6.2	854	8.5	11	4	0	8	0
149	MD27	99	14.6	5020	7.7	26	4	1	11	0
150	MD30	109	11.9	1317	8.5	19	5	1	13	0
151	MD33	93	13.4	3510	7.5	44	3	2	6	0
152	MD36	49	12.5	91	8.2	19	5	3	11	1
153	MD39	169	11.3	3210	8.2	7	3	1	8	0
154	MD44	101	21.0	5030	8.4	26	7	0	7	0
155	MD46	102	15.5	3870	7.3	18	5	0	3	1
156	MD49	78	17.3	5520	7.0	20	3	0	10	0
157	MD59	128	8.6	3000	7.2	32	10	1	8	0
158	MD74	26	20.0	2550	7.0	30	14	1	7	0
159	MD76	37	17.0	1212	6.2	30	10	6	13	2
160	MD78	113	10.9	3740	6.1	19	3	1	6	0
161	MD83	125	9.5	6760	6.5	25	8	5	28	0
162	NG18	55	10.6	57	9.3	2	1	0	7	3
163	NG41	25	17.1	88	9.1	5	0	4	4	2
164	NG47	200	2.1	50	8.7	2	2	2	5	3
165	NG63	21	10.6	43	8.4	7	1	2	3	3
166	NG86	30	11.8	37	8.2	7	1	1	6	2
167	NG89	45	12.6	58	8.0	2	3	3	8	4
168	NR18	58	9.0	44	8.4	2	0	2	7	4
169	NR41	16	22.0	70	9.3	11	0	2	10	3
170	NR47	62	13.3	45	8.0	2	1	2	6	5
171	NR63	33	20.3	268	8.2	3	0	1	8	4
172	NR74	41	25.9	228	8.4	1	0	0	8	0
173	NR86	23	41.4	303	7.6	2	2	2	9	2
174	NR89	30	17.8	41	8.0	6	1	3	8	3
175	GE05	72	13.0	74	8.6	11	0	0	12	3
176	GE09	71	9.0	27	7.9	6	0	3	12	5
177	GE13	133	3.2	20	7.6	4	0	1	9	2
178	GE17	47	13.1	52	7.9	8	0	1	9	2
179	GE19	110	10.2	33	7.8	7	0	5	13	9
180	GE21	327	3.2	32	7.8	9	1	7	9	4

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
181	GE28	93	10.9	69	8.4	3	0	1	10	2
182	GE43	50	13.4	73	7.7	10	1	3	8	4
183	GE46	94	7.0	26	7.6	3	0	1	6	4
184	GE49	70	6.6	42	7.5	15	0	6	15	4
185	GE60	141	3.8	25	7.5	6	0	4	12	2
186	GE62	78	5.0	22	7.5	4	0	6	8	4
187	GE63	152	6.6	30	7.5	3	0	4	7	1
188	GE66	96	7.4	31	7.4	3	0	0	10	3
189	GE72	424	4.2	24	7.4	8	0	8	5	3
190	GE73	71	9.7	93	7.3	5	0	8	5	2
191	GE80	390	2.8	18	7.9	3	0	3	1	4
192	GE82	71	8.6	44	7.4	6	0	3	6	2
193	GE92	25	8.2	20	7.3	3	0	0	4	4
194	GE99	41	9.7	146	8.1	13	0	3	11	3
195	NA01	108	16.8	76	9.6	5	1	3	7	1
196	NA08	39	14.7	72	9.3	6	0	2	8	2
197	NA09	62	13.4	124	9.2	4	0	1	5	0
198	NA11	165	4.8	86	9.8	3	0	3	10	4
199	NA17	431	4.2	35	8.8	2	0	2	7	1
200	NA19	49	13.9	80	8.1	1	1	3	5	1
201	NA23	14	9.4	115	9.5	6	0	2	2	1
202	NA25	82	5.3	68	9.8	3	0	2	5	0
203	NA30	69	11.4	121	9.2	6	0	3	8	2
204	NA31	753	1.5	43	9.4	6	0	6	7	1
205	NA37	424	2.6	36	8.7	3	0	8	4	0
206	NA45	83	6.1	44	8.5	6	0	2	7	3
207	NA53	39	6.8	38	8.5	7	1	2	10	2
208	NA57	51	8.6	56	7.9	2	0	1	7	2
209	NA59	25	11.6	34	7.9	7	0	7	5	3
210	NA77	51	7.8	28	7.5	8	0	3	8	3
211	NA79	39	18.6	49	7.5	3	0	1	3	1
212	NA89	199	4.2	27	7.5	9	0	2	8	2
213	NA94	97	3.8	39	8.0	8	0	4	6	2
214	NA97	315	3.1	35	7.7	6	1	3	14	5
215	O05	153	5.4	27	6.5	6	1	5	14	13
216	O06	108	9.3	24	6.3	4	3	2	10	6
217	O17	79	11.8	29	6.3	5	2	4	16	9
218	O18	174	9.8	43	6.6	6	2	6	11	4
219	O21	823	1.8	28	6.1	4	0	3	9	8
220	O30	164	5.0	63	6.6	4	3	5	13	7
221	O31	350	3.0	40	6.5	3	0	3	12	10
222	O38	104	8.3	35	6.5	7	2	4	12	6
223	O41	191	4.2	23	6.0	3	3	3	11	12
224	O44	183	6.8	22	6.1	8	1	3	14	12
225	O45	180	4.6	40	6.7	8	2	8	20	7

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
226	O58	138	10.2	47	6.8	10	3	6	14	5
227	O71	157	7.3	36	6.5	4	2	7	20	9
228	O73	106	4.8	23	6.4	13	2	7	23	12
229	O78	367	2.5	23	6.7	7	1	3	17	10
230	O89	138	6.4	32	6.4	5	1	4	13	6
231	O90	132	9.6	22	6.1	6	3	3	18	10
232	O95	126	4.7	21	6.1	7	2	5	14	8
233	O96	134	7.7	47	6.2	6	1	3	14	9
234	O98	76	11.3	71	6.8	15	2	8	15	11
235	E03	112	9.4	60	6.4	8	2	5	15	11
236	E12	101	9.4	226	6.6	7	4	5	12	8
237	E20	80	17.8	148	7.4	8	3	5	15	12
238	E21	145	11.3	37	7.2	13	2	6	14	11
239	E26	95	10.7	28	6.8	7	0	4	21	12
240	E32	140	9.8	37	6.4	10	3	6	12	10
241	E36	100	9.7	27	6.4	9	5	6	17	10
242	E44	94	11.7	44	6.0	9	3	3	11	9
243	E46	97	11.3	46	6.1	9	1	4	17	12
244	E49	102	8.8	29	6.1	6	1	5	16	12
245	E52	108	13.1	24	7.0	8	2	5	11	13
246	E61	118	10.1	31	6.8	13	4	6	11	9
247	E68	121	7.7	61	5.8	13	1	5	17	16
248	E69	168	8.8	133	6.0	6	2	2	13	7
249	E72	220	10.1	68	7.1	13	2	8	15	14
250	E77	108	7.4	79	6.0	8	2	4	20	10
251	E81	99	10.5	43	8.0	9	3	6	14	9
252	E83	36	10.4	158	8.4	4	3	3	12	6
253	E98	147	12.1	177	6.1	12	2	3	18	10
254	M00	396	1.4	8	6.5	1	1	6	4	6
255	M03	382	1.4	11	6.6	3	1	6	2	7
256	M05	319	1.7	9	6.5	1	1	5	4	7
257	M09	520	0.8	62	7.3	1	2	5	10	6
258	M14	322	1.4	11	6.9	1	2	8	1	8
259	M18	417	1.3	16	6.6	2	1	10	1	5
260	M23	394	2.0	12	6.3	2	0	12	4	8
261	M25	249	2.1	10	6.6	3	0	11	3	8
262	M36	311	2.0	39	6.3	1	1	11	6	6
263	M39	392	2.1	11	6.8	1	0	9	4	8
264	M41	261	2.1	19	6.7	2	0	17	0	8
265	M42	230	3.5	22	6.4	2	0	14	1	5
266	M52	260	2.9	31	6.7	2	1	15	0	7
267	M53	187	2.9	16	6.9	3	0	14	1	4
268	M60	331	1.4	10	6.7	1	1	15	0	6
269	M72	232	2.2	8	6.3	2	1	10	3	9
270	M77	458	1.4	15	6.3	0	0	6	4	8

N	Sample	Infiltrability	Silt+Clay	EC	pH	Species number				
		mm hr^{-1}	%	mS m^{-1}		Chamaephytes	Geophytes	Phanerophytes	Therophytes	Hemicryptophytes
271	M85	602	1.0	13	6.0	1	1	7	7	4
272	M87	401	1.4	11	6.0	1	1	3	5	5
273	M89	273	0.8	11	6.1	1	0	2	4	4
274	MU06	461	1.2	12	6.4	1	1	4	4	7
275	MU15	449	1.2	12	6.4	1	1	6	3	6
276	MU17	530	0.9	11	6.3	1	2	4	1	5
277	MU24	365	1.2	12	5.6	0	1	9	2	7
278	MU32	248	2.1	22	6.5	3	1	7	2	8
279	MU40	463	2.2	41	7.0	0	2	10	7	6
280	MU41	177	2.7	18	6.9	1	1	8	3	10
281	MU44	239	2.7	12	6.7	1	1	11	2	3
282	MU47	235	2.2	14	6.8	1	1	11	2	5
283	MU52	428	1.2	12	6.4	1	0	7	7	6
284	MU53	384	2.6	28	6.8	1	0	13	2	7
285	MU55	394	3.5	28	7.0	1	0	10	4	9
286	MU59	242	2.5	13	6.9	2	2	14	4	10
287	MU63	203	2.7	22	6.7	0	1	9	2	4
288	MU64	348	2.9	27	6.8	1	1	8	4	4
289	MU69	209	2.2	19	6.8	2	2	10	4	7
290	MU72	444	1.8	10	6.4	1	0	8	5	6
291	MU76	401	2.5	14	6.5	0	1	6	2	9
292	MU89	479	1.0	12	6.2	2	1	8	6	8
293	MU93	598	1.6	9	6.2	2	2	4	9	7
294	S00	437	0.9	16	5.5	2	1	15	7	6
295	S11	405	1.1	10	5.8	1	0	8	1	4
296	S15	475	1.4	8	5.9	1	0	12	2	5
297	S21	376	1.4	7	5.8	1	0	11	6	4
298	S25	523	1.3	10	5.7	4	0	10	4	4
299	S31	444	1.5	7	5.7	3	0	10	3	6
300	S42	394	1.8	9	5.6	1	0	8	4	5
301	S49	492	1.4	8	5.8	2	0	12	2	6
302	S51	299	1.6	7	5.6	3	0	5	5	7
303	S52	412	1.3	12	5.5	2	0	7	6	5
304	S56	439	1.4	8	5.6	3	0	13	3	7
305	S69	324	1.6	7	5.6	1	0	12	4	4
306	S71	198	6.1	17	6.6	6	3	9	3	6
307	S72	194	4.6	24	6.7	8	3	9	6	5
308	S73	139	4.4	24	6.9	4	3	8	4	8
309	S77	353	5.0	34	7.0	2	2	3	6	8
310	S84	258	5.3	17	7.0	7	4	11	4	9
311	S89	151	5.8	36	6.9	5	3	11	7	12
312	S95	186	3.4	15	6.9	9	1	10	2	8
313	S96	324	2.5	15	6.6	3	1	7	2	9

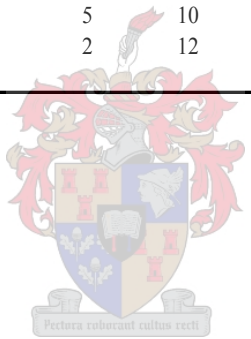
Appendix B2. The quantile values (0.95 and 0.1) for the species richness data grouped into classes according to independent soil variables: infiltrability (B2.1.), water-dispersible clay+silt (B2.2.), EC (B2.3.), and pH (B2.4.).

Appendix B2.1.

Class No.	Sample No. in each class	Mean Infiltrability mm hr^{-1}	Chamaephytes		Geophytes		Phanerophytes		Therophytes		Hemicryptophytes	
			quantile values									
			0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1
1	15	18	30	4	11	0	4	0	9	1	3	0
2	15	29	24	4	9	0	7	0	8	1	3	0
3	15	36	22	1	3	0	8	0	15	2	4	0
4	15	40	22	3	10	0	4	0	15	3	3	0
5	15	48	28	2	16	0	4	1	20	6	4	0
6	15	60	33	2	12	0	3	0	15	4	4	0
7	15	72	27	5	14	0	8	0	16	5	7	0
8	15	80	32	3	12	0	6	1	18	4	10	0
9	15	90	32	4	8	0	5	1	23	6	10	0
10	15	98	28	5	9	0	6	0	17	3	11	0
11	15	105	23	5	8	1	6	0	24	7	13	0
12	15	118	26	7	11	0	5	1	26	8	13	0
13	15	134	34	4	9	0	7	1	18	3	9	0
14	15	151	18	4	4	0	8	1	24	3	12	0
15	15	175	17	3	3	0	11	1	22	2	12	0
16	15	211	24	2	5	0	11	2	16	2	11	0
17	15	256	20	1	3	0	16	2	9	1	9	0
18	15	331	10	1	2	0	13	3	13	1	9	0
19	15	394	4	1	1	0	12	3	9	1	9	4
20	15	442	10	0	2	0	14	2	8	3	7	1
21	12	567	8	1	2	0	12	2	9	2	8	1

Appendix B2.2.

Class No.	Sample No. in each class	Mean Silt + clay %	Chamaephytes		Geophytes		Phanerophytes		Therophytes		Hemicryptophytes	
			quantile values									
			0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1
1	15	0.9	12	1	2	0	10	2	8	2	7	0
2	15	1.2	11	1	1	0	12	2	6	2	7	0
3	15	1.5	7	1	2	0	14	2	8	1	8	0
4	15	2.0	9	1	2	0	14	3	10	2	8	1
5	15	2.5	12	0	2	0	13	3	14	2	10	0
6	15	3.1	28	2	11	0	14	2	25	1	11	1
7	15	3.6	25	4	17	0	11	1	20	3	6	0
8	15	4.2	30	3	10	0	8	2	18	3	9	0
9	15	4.8	33	3	10	0	8	1	24	6	11	0
10	15	5.3	25	3	12	0	11	1	19	5	12	0
11	15	6.3	22	4	8	0	8	0	21	7	9	0
12	15	7.1	19	3	4	0	6	0	21	4	9	0
13	15	7.9	22	3	10	0	4	1	19	4	11	0
14	15	8.8	33	2	13	0	5	1	19	6	8	0
15	15	9.5	23	3	7	0	7	1	21	3	10	0
16	15	10.2	19	3	4	0	7	1	14	1	11	0
17	15	10.9	22	2	6	0	6	0	18	3	6	0
18	15	11.6	24	6	4	0	7	1	17	4	11	0
19	15	13.1	28	1	5	0	4	0	11	3	7	0
20	15	16.5	30	5	10	0	5	0	14	3	6	0
21	13	24.7	33	2	12	0	3	0	14	0	3	0

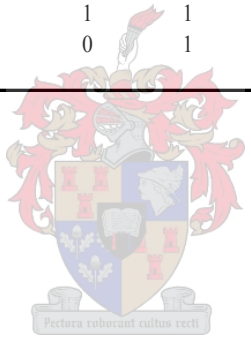


Appendix B2.3.

Class No.	Sample No. in each class	Mean EC mS m^{-1}	Chamaephytes		Geophytes		Phanerophytes		Therophytes		Hemicryptophytes	
			quantile values									
			0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1
1	15	8	3	1	1	0	12	4	7	1	8	4
2	15	11	3	0	2	0	13	2	6	0	8	4
3	15	15	8	0	3	0	14	3	7	1	10	3
4	15	22	14	0	3	0	15	0	17	0	12	1
5	15	25	26	1	10	0	8	1	19	4	13	2
6	15	30	25	1	14	0	14	0	18	0	12	1
7	15	35	28	2	15	0	9	1	19	4	11	0
8	15	39	35	0	16	0	10	1	21	6	10	1
9	15	43	27	3	12	0	6	0	15	3	9	1
10	15	50	25	2	12	0	6	0	18	3	10	1
11	15	65	20	1	5	0	8	1	16	4	15	0
12	15	80	21	1	7	0	4	0	17	4	6	0
13	15	92	20	1	5	0	7	0	17	4	4	0
14	15	113	29	1	9	0	7	2	27	2	6	0
15	15	137	19	0	8	0	6	0	15	3	8	0
16	15	165	20	4	3	0	6	1	22	3	7	0
17	15	208	24	1	6	0	5	0	22	2	5	0
18	15	291	23	2	6	0	5	1	21	1	4	0
19	15	704	32	11	7	0	5	0	13	0	1	0
20	15	2009	31	4	11	0	5	0	13	0	1	0
21	13	4698	34	9	7	1	4	0	27	3	3	0

Appendix B2.4.

Class No.	Sample No. in each class	Mean pH	Chamaephytes		Geophytes		Phanerophytes		Therophytes		Hemicryptophytes	
			quantile values									
			0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1	0.95	0.1
1	15	5.4	30	0	10	0	14	1	11	0	7	0
2	15	5.9	20	1	5	0	12	1	18	1	13	1
3	15	6.1	24	1	5	0	7	1	18	3	12	0
4	15	6.3	23	0	10	0	13	2	19	1	9	1
5	15	6.5	19	1	7	0	7	1	25	2	12	0
6	15	6.6	25	0	9	0	10	0	21	1	9	0
7	15	6.7	17	0	3	0	16	2	19	0	9	0
8	15	6.8	24	1	14	0	14	0	19	0	11	0
9	15	7.0	32	0	11	0	11	0	12	1	12	0
10	15	7.2	27	8	12	0	7	1	19	3	12	0
11	15	7.4	31	1	11	0	8	0	17	1	8	0
12	15	7.5	39	3	13	0	6	0	15	3	4	0
13	15	7.7	24	2	10	0	6	0	21	3	4	0
14	15	7.9	26	2	8	0	6	0	17	2	9	0
15	15	8.2	19	1	9	0	4	0	26	3	7	0
16	15	8.5	27	1	6	0	3	0	16	3	5	0
17	15	8.9	28	2	4	0	9	0	23	3	3	0
18	15	9.3	19	1	2	0	4	0	10	1	3	0
19	15	9.5	10	2	3	0	4	0	11	2	3	0
20	15	9.7	13	1	1	0	4	0	14	2	3	0
21	13	9.9	11	0	1	0	4	0	10	3	4	0



Appendix B3. Soil infiltrability and contents of particle size fractions determined by the laser technique for 177 samples.

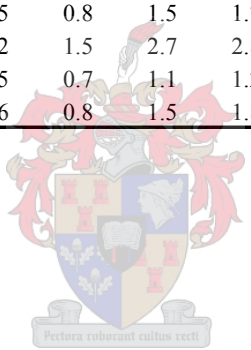
N	Sample	Infiltrability	Particle size fraction content (%) at size intervals (μm)										
		mm hr^{-1}	0-2	2-5	5-10	10-20	20-30	30-50	50-70	70-100	100-120	120-200	>200
1	E20	85	6.5	8.0	7.3	10.1	8.0	9.2	5.2	3.0	0.1	1.2	40.9
2	E44	65	5.5	8.3	9.8	16.0	13.1	13.5	7.0	4.0	1.2	1.0	20.5
3	E69	179	3.6	3.3	4.6	7.7	10.9	3.3	4.5	9.4	2.2	21.8	28.7
4	E72	254	5.6	9.2	7.1	6.6	4.1	4.0	3.2	3.0	2.5	10.8	43.8
5	E83	58	4.8	8.0	9.0	12.7	10.8	13.7	9.1	4.2	0.3	1.6	25.7
6	E98	115	6.2	9.2	11.1	17.4	13.8	13.7	6.3	1.7	0.3	1.0	19.2
7	K09	49	3.3	4.3	5.3	8.7	9.3	16.7	12.5	6.9	2.4	3.5	27.1
8	K22	43	3.2	4.2	4.8	6.8	6.8	12.4	9.8	5.4	1.8	2.7	42.1
9	K34	147	2.1	3.6	4.4	6.1	5.8	11.3	10.2	7.0	2.8	4.0	42.7
10	K56 off mond	39	2.9	4.0	4.6	7.1	7.5	13.7	9.8	5.0	1.5	1.1	42.8
11	K56 on mond	66	4.0	5.4	6.1	8.8	8.6	15.2	11.1	5.9	1.8	0.5	32.7
12	K59	60	2.9	4.1	5.1	8.2	8.8	15.3	10.7	5.5	1.9	1.4	36.1
13	M09	521	0.4	0.3	0.6	1.0	0.9	1.4	1.3	2.3	2.4	21.9	67.5
14	M42	275	1.5	2.1	2.3	3.3	2.7	3.3	2.9	3.7	3.2	23.1	52.0
15	M53	221	1.4	1.9	2.1	3.2	2.5	2.8	2.4	3.4	2.9	22.2	55.1
16	M72	312	1.3	1.0	1.0	1.8	1.6	2.4	2.8	4.1	3.7	26.8	53.5
17	M77	573	0.5	0.4	0.5	0.8	0.7	1.1	1.1	1.8	1.8	16.5	74.9
18	M85	880	0.7	0.8	1.1	2.1	2.3	3.3	3.0	3.9	3.0	18.0	61.8
19	MU17	1008	0.5	0.4	0.6	1.0	0.9	1.5	1.6	2.5	2.3	20.3	68.5
20	MU40	817	0.9	1.1	1.2	1.8	1.7	2.3	2.5	3.1	2.8	22.6	60.1
21	MU41	434	1.0	1.7	2.0	3.1	2.8	3.8	3.1	4.0	3.4	24.9	50.4
22	MU63	272	1.1	1.2	1.6	2.4	2.3	3.1	2.9	4.3	4.1	31.1	45.8
23	MU69	354	1.3	1.5	1.8	2.8	2.5	3.8	4.4	6.9	6.2	36.9	31.9
24	MU93	700	0.7	0.7	0.7	1.4	1.3	2.1	2.7	3.7	3.6	26.4	56.5
25	N12	97	1.7	2.4	3.3	6.4	7.1	12.9	10.6	6.7	2.7	3.2	43.0
26	N66	89	4.2	4.5	6.4	9.5	11.2	12.4	14.1	16.1	1.2	18.0	2.4
27	N81 AJM	54	8.8	9.7	10.0	11.4	10.4	11.8	18.2	11.9	1.7	4.6	1.5
28	N84	77	1.6	2.0	2.9	5.8	6.6	13.2	11.9	7.8	2.9	3.6	41.9
29	N98	39	3.8	5.6	6.6	9.7	9.7	17.6	15.4	9.9	4.4	2.5	14.9
30	S15	897	1.2	0.9	1.0	1.5	1.3	2.0	2.6	3.9	3.9	30.2	51.4
31	S25	566	1.3	1.2	1.2	1.7	1.4	2.1	2.6	3.6	3.4	25.3	56.1
32	S49	881	0.8	0.7	0.7	1.2	1.1	1.9	2.4	3.5	3.4	25.4	58.9
33	S71	227	3.8	8.0	8.3	12.9	12.1	15.5	10.2	6.9	3.4	10.0	9.0
34	S73	276	1.4	2.4	2.4	3.7	3.5	4.9	3.9	4.2	3.4	22.8	47.3
35	S89	112	1.3	2.3	2.3	3.4	3.2	4.1	3.1	3.3	3.1	23.3	50.5
36	W22	90	3.1	3.5	3.7	5.1	4.6	6.0	6.8	9.7	7.5	23.1	27.0
37	W40	191	3.8	4.7	5.9	8.2	5.9	8.3	4.5	10.3	4.0	23.4	21.0
38	W70	147	3.6	3.3	3.2	3.9	3.4	4.4	5.5	7.9	6.9	24.7	33.2
39	W72	135	7.9	10.8	12.5	14.5	9.9	10.1	9.7	9.1	3.7	8.3	3.5
40	W91	231	1.6	2.9	3.9	5.9	5.0	7.0	6.4	7.6	5.6	18.7	35.3
41	W95	225	1.5	2.3	2.5	3.4	3.2	4.5	4.7	5.9	4.8	19.2	48.0
42	Y03	161	0.9	1.0	1.1	1.7	2.3	7.2	7.9	5.8	2.1	8.8	61.2
43	Y67	179	0.8	0.8	0.8	1.1	1.4	4.5	6.1	5.0	2.4	9.9	67.2
44	Y76	1288	0.7	0.6	1.2	0.3	0.4	1.7	4.1	5.6	3.4	13.9	68.1
45	Y84	927	0.3	0.2	0.1	0.2	0.3	1.6	2.8	3.0	1.6	10.9	78.9
46	Y92	1434	0.4	0.2	0.2	0.2	0.2	1.0	2.1	2.7	1.7	10.0	81.4
47	Y98	253	0.4	0.4	0.4	0.6	0.9	3.6	4.6	3.4	1.7	8.8	75.2
48	SMC2	101	3.0	3.9	4.1	6.5	6.5	8.6	6.3	5.2	3.4	11.1	41.4
49	SMC5	183	1.4	1.7	1.8	2.7	2.2	3.1	3.3	4.2	3.3	17.0	59.5
50	SMC6	38	6.5	6.1	5.9	6.9	4.9	4.7	4.6	4.3	3.7	15.9	36.5
51	SMD5	211	1.8	2.2	2.2	3.0	2.4	4.0	4.8	6.0	4.7	19.8	49.2

Appendix B3, page 2.

N	Sample	Infiltrability	Particle size fraction content (%) at size intervals (μm)										
		mm hr^{-1}	0-2	2-5	5-10	10-20	20-30	30-50	50-70	70-100	100-120	120-200	>200
52	SMD6	42	8.0	8.7	8.1	9.0	6.2	5.7	4.8	4.4	3.2	10.8	31.1
53	SME6	37	10.4	12.7	15.2	21.6	8.6	12.7	9.8	4.2	1.4	2.2	1.2
54	NR14	52	14.4	14.1	14.2	15.8	9.7	13.4	6.3	6.7	1.7	2.5	1.2
55	NR16	69	12.1	13.4	14.0	16.5	10.7	12.8	11.8	4.9	0.6	2.0	1.2
56	NR37	72	9.1	6.9	5.5	5.9	4.3	6.0	5.0	6.5	4.5	20.7	25.6
57	NR41	23	12.0	9.4	5.4	4.6	3.0	5.1	4.8	4.8	3.9	13.4	33.6
58	NR57	28	6.6	7.0	5.8	7.2	5.6	7.5	5.8	7.3	4.6	21.6	20.9
59	NR86	16	12.2	10.0	10.0	13.0	10.5	10.6	5.6	3.6	2.1	6.0	16.4
60	NG15	73	13.0	12.9	13.2	15.1	6.8	10.3	14.6	6.8	1.2	4.6	1.5
61	NG34	93	7.6	4.9	4.0	4.3	3.5	6.6	7.5	9.3	6.5	25.0	20.8
62	NG35	172	2.7	3.4	2.5	2.7	2.3	5.3	6.7	8.8	6.3	28.8	30.5
63	NG41	30	11.5	7.2	5.4	5.0	3.2	5.9	6.7	9.6	6.7	23.6	15.1
64	NG63	41	13.4	12.9	12.9	15.8	7.4	16.4	8.4	7.7	1.5	3.6	0.0
65	NG77	30	12.5	12.3	13.5	17.8	11.4	13.0	11.1	4.7	1.3	2.4	0.0
66	C44	99	2.0	3.7	4.2	5.4	4.8	7.8	8.5	9.9	6.9	27.3	19.6
67	C51	144	1.6	3.0	3.7	5.4	5.2	9.2	9.3	10.4	6.9	27.9	17.3
68	C52	135	2.0	3.4	4.0	5.7	5.2	8.6	8.2	9.6	6.7	27.9	18.7
69	C76	183	1.3	2.5	4.4	8.6	7.8	13.9	12.7	21.0	2.4	22.6	2.8
70	C91	191	2.1	2.7	3.6	5.7	5.5	9.8	9.2	10.0	6.5	26.6	18.2
71	C94	159	1.0	2.1	2.6	4.0	4.0	7.2	7.2	7.6	5.0	20.1	39.1
72	D02	80	2.7	3.8	5.2	6.7	8.9	5.5	7.3	9.0	3.5	26.3	21.1
73	D74	116	2.1	3.0	4.3	6.0	8.4	7.7	7.4	13.1	6.7	26.9	14.4
74	NA01	51	13.8	13.2	12.0	15.3	8.5	13.0	11.5	7.2	1.7	3.6	0.2
75	NA17	353	2.4	1.8	1.7	2.5	2.4	3.1	2.8	2.5	1.7	6.1	72.8
76	NA23	44	5.5	4.3	3.3	3.6	3.0	4.2	3.6	3.9	2.5	11.1	54.9
77	NA31	2343	1.1	0.9	0.7	0.7	0.5	0.6	0.5	0.8	0.9	5.0	88.4
78	NA59	41	4.2	4.3	3.4	4.2	3.8	5.9	4.8	5.4	3.0	10.5	50.4
79	NA79	66	9.7	7.0	4.7	5.0	3.7	4.4	3.0	3.5	1.9	8.4	48.7
80	GA08	67	3.7	4.6	4.2	4.9	4.0	7.1	7.3	7.7	5.4	18.1	33.0
81	GA21	49	8.3	7.1	6.2	7.0	5.9	8.6	8.7	7.7	5.1	15.3	20.2
82	GA37	23	9.4	8.0	7.0	7.7	6.3	8.0	7.9	6.4	4.3	11.9	23.0
83	GA57	62	6.6	4.5	4.4	4.9	4.0	6.0	7.0	6.9	5.4	19.3	31.0
84	GO30	350	1.0	0.7	0.7	1.2	1.6	4.7	9.8	16.9	14.5	39.4	9.5
85	GO37	280	1.0	0.9	0.9	1.5	1.7	4.8	9.4	15.7	13.6	39.4	11.1
86	GO51	266	1.2	0.9	0.9	1.3	1.4	3.7	6.8	12.2	11.9	41.6	18.2
87	GO56	231	1.1	0.8	0.7	1.2	1.5	4.4	8.6	14.6	13.2	38.8	15.2
88	GO80	346	0.8	0.6	0.5	0.8	1.1	3.9	8.4	15.7	14.0	38.7	15.6
89	GO85	256	1.0	0.8	0.9	1.8	3.4	4.6	7.6	16.2	8.2	39.0	16.5
90	R 14	89	2.4	5.0	5.9	7.8	7.1	11.1	10.3	9.2	5.6	13.9	21.7
91	R 38	98	2.4	4.6	5.8	8.1	6.8	10.9	9.5	9.1	5.6	19.2	17.9
92	R 46	149	1.8	2.7	3.1	4.2	3.9	6.9	7.1	7.9	5.4	24.0	32.9
93	R 60	99	3.2	2.8	3.3	4.9	5.0	9.0	8.6	8.6	5.2	18.3	31.1
94	R 81	77	1.5	2.6	3.3	5.0	4.7	8.5	8.8	9.2	5.8	22.4	28.1
95	R 98	140	2.0	3.3	3.7	4.8	4.3	7.2	7.4	7.9	5.4	22.9	31.1
96	R98 sand	934	0.5	0.5	0.6	0.6	0.5	0.8	0.9	1.3	1.2	10.9	82.2
97	G15	146	1.5	1.5	1.7	2.7	3.0	5.3	5.2	4.9	2.8	9.8	61.7
98	G16	97	1.8	1.4	1.5	2.2	2.3	4.2	4.0	3.9	2.4	8.9	67.2
99	G26	86	1.5	2.0	1.9	2.6	2.5	4.8	5.5	5.4	3.5	11.6	58.7
100	G52	70	2.3	3.4	3.5	4.9	4.3	6.1	5.5	4.3	2.7	8.3	54.8
101	G62	314	1.5	2.0	2.5	3.5	3.9	6.7	4.8	6.0	2.5	12.2	54.4
102	G82	120	1.5	2.0	1.9	2.7	3.0	6.2	6.6	6.6	4.0	13.0	52.5

N	Sample	Infiltrability	Particle size fraction content (%) at size intervals (μm)										
		mm hr^{-1}	0-2	2-5	5-10	10-20	20-30	30-50	50-70	70-100	100-120	120-200	>200
103	GE17	77	7.0	5.2	3.5	3.7	3.0	4.9	3.9	4.1	2.4	7.5	54.6
104	GE19	74	6.9	6.2	5.2	6.1	5.4	7.2	5.8	3.5	1.6	2.6	49.4
105	GE21	257	3.8	2.3	1.7	1.7	1.2	2.0	1.9	2.9	2.0	10.6	70.0
106	GE80	1716	0.9	1.0	0.9	1.1	0.9	1.4	1.3	1.5	1.0	5.5	84.5
107	GE82 rocky	35	14.9	13.7	13.5	15.4	9.3	14.6	8.8	5.7	4.1	0.0	0.0
108	NAR36	55	6.8	6.6	6.2	6.8	6.0	7.7	8.4	8.6	6.5	22.9	13.6
109	NAR55	87	4.3	7.4	7.6	8.8	7.5	10.2	10.9	10.1	7.2	20.0	5.9
110	NAR82	103	2.1	3.0	4.2	6.0	6.2	8.0	9.0	11.3	3.8	23.2	23.2
111	NAR91	95	3.9	6.4	6.4	8.0	6.9	10.7	11.2	10.7	7.3	18.4	10.0
112	O41	652	2.1	2.6	2.3	2.3	1.8	2.2	3.2	3.6	3.3	14.5	62.0
113	O71fr mond	151	6.5	7.8	5.4	6.0	5.5	6.5	6.1	4.4	3.4	11.1	37.3
114	O71old mond	193	8.3	7.4	5.8	7.0	6.4	8.2	7.7	5.5	3.5	10.4	29.7
115	O78	262	1.0	1.4	1.4	1.6	1.2	1.7	1.9	3.0	2.2	11.9	72.7
116	O96	87	8.0	9.8	12.2	17.5	9.3	16.7	10.0	5.9	4.0	2.9	3.7
117	O98	62	6.9	9.3	12.8	20.2	12.0	17.3	10.4	6.2	1.7	1.9	1.3
118	GH03	26	12.3	15.2	16.0	17.4	9.9	10.3	4.9	4.2	2.2	6.0	1.6
119	GH13	24	10.7	12.6	15.2	17.8	11.8	10.7	5.7	4.4	2.5	6.5	2.1
120	GH50 east	25	6.6	11.1	14.1	17.5	12.9	12.3	7.5	4.8	2.9	7.4	2.8
121	GH50 west	23	13.5	18.7	19.2	18.6	9.6	8.9	3.6	2.8	1.4	3.5	0.1
122	GH61	21	8.4	12.7	13.0	13.6	10.1	10.1	7.7	5.3	3.6	10.6	4.9
123	GH68	26	5.9	10.6	12.8	16.6	13.7	14.0	9.5	5.1	3.0	6.5	2.4
124	MD02	42	2.6	4.8	6.4	12.3	14.6	23.2	15.1	10.0	3.7	7.1	0.1
125	MD06 sand	515	3.5	3.5	3.3	3.4	2.7	4.5	5.9	7.4	6.2	28.2	31.4
126	MD23	137	9.5	10.3	9.8	10.6	8.8	11.0	10.6	8.7	5.7	12.7	2.3
127	MD60 quartz	90	11.8	11.1	9.7	10.4	7.5	8.2	7.8	7.1	4.2	15.4	6.7
128	MD60 sand	144	2.4	3.6	3.5	4.2	3.3	6.7	9.9	12.0	9.1	31.4	14.0
129	MD74	37	9.5	9.3	9.2	10.3	9.0	12.7	12.1	8.9	4.5	12.2	2.3
130	RG00	29	11.9	14.3	14.1	13.2	9.1	9.0	7.2	4.8	3.1	9.7	3.5
131	RG03	51	7.5	10.1	9.2	9.6	7.1	8.5	7.9	7.5	5.2	18.0	9.5
132	RG38	37	6.1	10.8	13.2	16.3	12.0	11.5	8.5	5.6	3.7	9.9	2.4
133	RG57	135	4.0	5.9	6.2	7.4	6.6	9.4	9.8	9.8	7.3	23.3	10.1
134	RG94	45	5.7	8.4	9.9	11.3	9.1	12.1	9.4	8.9	5.1	13.6	6.7
135	RG96	181	3.8	4.4	5.3	7.4	7.6	12.3	10.5	10.3	6.5	20.6	11.4
136	A 01	2171	0.5	0.2	0.1	0.1	0.1	0.4	0.8	1.9	2.4	25.5	68.0
137	A 28	325	1.2	1.2	1.1	1.0	0.8	1.7	3.4	6.9	6.2	34.2	42.3
138	A 51	159	1.4	1.9	1.7	1.6	1.0	2.5	4.4	7.6	6.6	28.3	43.2
139	A 68	276	1.1	1.2	1.1	1.2	1.0	2.5	4.5	8.2	6.8	35.4	37.0
140	A 78	2202	0.6	0.2	0.2	0.1	0.2	0.8	1.6	3.3	3.4	28.3	61.4
141	A 81	434	1.2	1.2	1.4	1.5	1.0	1.9	3.3	6.3	5.4	27.3	49.6
142	RH 07	79	3.7	3.6	3.6	4.3	3.1	3.6	3.4	2.9	2.7	11.8	57.4
143	RH 22	349	1.5	1.6	1.7	2.1	1.7	2.7	2.8	3.1	2.8	14.9	65.0
144	RH 46	213	1.4	1.6	1.6	2.1	1.8	2.7	2.3	2.1	1.8	10.6	72.0
145	RH 64	74	3.8	4.2	3.4	3.7	2.7	3.8	3.3	3.6	2.5	11.2	57.7
146	RH 65	83	3.5	3.8	3.3	3.5	3.0	4.8	5.5	5.7	4.4	18.7	43.7
147	RH 87	82	7.8	10.2	11.3	13.0	9.8	11.2	6.3	3.3	1.3	2.2	23.8
148	PK01	48	2.3	3.4	3.3	4.2	3.2	4.2	3.6	3.7	2.7	14.7	54.5
149	PK24	73	2.8	3.4	3.4	4.0	3.2	4.1	3.7	2.8	2.0	7.4	63.2
150	PK44	97	5.1	3.7	3.9	4.0	3.2	3.6	3.8	3.2	2.9	12.7	53.9
151	PK62	325	1.7	2.4	2.7	4.0	3.4	4.0	3.0	2.7	2.0	8.5	65.5
152	PK94	87	2.0	2.8	2.8	3.5	2.9	3.9	3.4	3.3	2.5	11.3	61.7
153	PK96	105	2.2	2.7	2.8	3.5	2.8	3.9	3.7	3.9	3.1	15.6	55.7
154	SN11	94	2.2	2.6	2.8	3.7	3.3	5.0	5.4	6.2	4.9	19.0	44.9

N	Sample	Infiltrability	Particle size fraction content (%) at size intervals (μm)										
		mm hr^{-1}	0-2	2-5	5-10	10-20	20-30	30-50	50-70	70-100	100-120	120-200	>200
155	SN41	101	3.3	2.5	2.6	3.4	2.8	3.8	4.0	4.4	3.5	15.6	54.1
156	SN80	76	3.4	3.1	3.2	4.4	4.1	7.4	8.4	8.3	5.4	17.1	35.2
157	SN84	119	4.8	5.1	4.4	4.2	3.5	5.3	5.9	5.9	4.1	14.6	42.1
158	SN86	135	3.6	3.5	3.2	3.5	2.6	3.7	3.6	3.6	2.7	11.6	58.4
159	SN92	88	4.4	3.2	3.1	3.6	3.0	4.9	5.9	6.5	5.0	19.0	41.5
160	EB09	312	1.6	2.0	2.2	3.0	2.6	2.8	3.2	3.1	2.9	16.1	60.6
161	EB40	66	4.0	5.2	5.9	7.7	6.5	6.7	4.0	4.4	2.4	10.6	42.6
162	EB59	107	5.6	3.0	3.5	4.5	4.0	4.3	3.4	4.5	3.2	17.0	46.9
163	EB68	94	2.9	3.3	3.9	4.7	3.5	3.3	3.3	3.7	2.9	13.1	55.4
164	EB74	146	3.1	3.4	4.0	4.4	3.1	2.4	2.1	2.3	1.8	11.1	62.2
165	EB90	179	2.1	2.6	3.3	3.9	2.9	2.5	1.8	2.7	2.0	12.5	63.7
166	CP02	1519	0.1	0.2	0.3	0.7	0.8	1.8	2.2	2.8	2.1	9.6	79.3
167	CP51	1008	0.3	0.3	0.4	0.9	1.4	3.1	3.4	3.9	3.1	17.6	65.6
168	CP59	1812	0.1	0.1	0.1	0.3	0.4	0.9	1.1	1.4	1.3	6.9	87.4
169	CP67	1370	0.3	0.2	0.3	0.7	0.8	1.6	1.7	2.4	2.2	18.3	71.5
170	CP91	1232	0.3	0.3	0.5	1.3	2.0	4.1	4.1	4.2	3.4	22.0	57.8
171	CP96	3228	0.2	0.3	0.4	0.9	1.0	1.7	1.7	2.4	2.1	17.9	71.3
172	RL03	575	0.6	0.4	0.5	0.9	0.9	2.1	3.1	4.9	4.2	28.0	54.3
173	RL13	518	0.6	0.4	0.6	1.0	1.0	2.2	3.0	4.6	3.5	23.9	59.1
174	RL16	336	1.1	0.5	0.8	1.5	1.7	2.6	2.7	3.0	2.7	16.4	67.0
175	RL31	248	1.0	1.2	1.5	2.7	2.8	4.4	4.8	5.4	4.1	25.3	46.7
176	RL45	781	0.6	0.5	0.7	1.1	1.2	2.5	3.3	4.7	3.8	25.1	56.4
177	RL91	378	0.7	0.6	0.8	1.5	1.8	3.6	4.3	4.9	3.5	19.7	58.6



Appendix B4. The quantile values (0.95 and 0.1) for the infiltrability data grouped into classes according to the contents of soil fractions of different size determined by laser analyser.

Class No.	Sample No.	Soil fractions of following size intervals (μm)																	
		0-2			2--5			5-10			10-20			20-30			30-50		
		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile	
		%	0.95	0.1	%	0.95	0.1	%	0.95	0.1	%	0.95	0.1	%	0.95	0.1	%	0.95	0.1
1	10	0	2591	494	0	2766	1000	0	2766	860	0	2188	860	0	2280	548	1	2280	567
2	10	1	2188	567	0	974	328	1	1843	501	1	2830	344	1	2547	243	2	2459	262
3	10	1	1340	161	1	1105	226	1	744	226	1	1498	226	1	890	262	2	861	158
4	10	1	1484	246	1	2061	256	1	1523	265	2	748	161	2	922	226	3	906	210
5	10	1	748	176	1	398	141	2	396	141	2	851	201	2	1074	155	3	654	92
6	10	1	297	117	2	335	85	2	398	117	3	398	117	3	442	85	4	398	86
7	10	2	339	77	2	303	100	3	505	100	3	425	99	3	351	42	4	792	48
8	10	2	186	96	3	463	86	3	148	77	4	303	71	3	190	71	5	441	78
9	10	2	517	48	3	165	87	3	364	44	4	155	48	3	303	87	5	278	72
10	10	3	160	43	3	361	68	4	170	79	5	143	58	4	287	60	6	137	40
11	10	3	364	73	4	124	43	4	193	67	5	213	63	5	190	67	7	277	67
12	10	4	243	64	4	187	44	5	181	43	6	207	74	6	191	41	8	159	28
13	10	5	109	44	5	128	39	6	188	28	7	188	37	7	167	41	9	166	28
14	10	6	207	28	7	149	30	6	166	42	8	187	47	7	182	40	10	170	20
15	10	7	116	48	8	242	40	8	242	35	10	116	39	9	127	37	11	142	35
16	10	9	168	23	10	114	22	11	127	42	13	186	20	10	113	25	13	143	36
17	10	11	81	22	12	115	24	13	107	25	16	95	26	11	138	20	14	152	34
18	7	14	67	27	15	64	24	15	48	24	19	79	24	13	194	25	18	185	40

Class No.	Sample No.	Soil fractions of following size intervals (μm)														
		50-70			70-100			100-120			120-200			>200		
		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile		Fraction content Mean	Infiltrability mm hr^{-1} quantile	
		%	0.95	0.1	%	0.95	0.1	%	0.95	0.1	%	0.95	0.1	%	0.95	0.1
1	10	1	2280	567	2	2266	143	1	2061	64	1	102	35	1	66	30
2	10	2	2459	176	3	2459	68	1	1642	30	3	92	31	2	115	25
3	10	3	914	308	3	878	84	2	474	51	4	2061	16	6	295	28
4	10	3	743	108	3	1608	73	2	982	56	7	1155	24	12	235	38
5	10	3	723	78	4	678	45	2	2392	47	9	982	30	17	310	89
6	10	4	679	42	4	958	63	2	1335	42	10	904	23	21	151	28
7	10	4	1263	94	4	800	26	3	606	68	11	931	42	28	187	57
8	10	5	297	37	5	662	25	3	950	26	12	291	25	32	442	40
9	10	5	147	25	5	486	25	3	778	41	14	1002	25	38	256	58
10	10	6	364	28	6	795	37	3	1791	219	16	466	42	43	250	43
11	10	7	250	50	6	380	59	4	525	36	18	2392	52	47	274	73
12	10	7	212	28	7	341	61	4	845	34	19	309	64	52	689	91
13	10	8	277	23	7	387	47	4	439	28	22	1131	32	55	571	48
14	10	9	173	37	8	219	48	5	219	49	23	276	59	58	1074	78
15	10	10	319	38	9	156	44	6	342	67	25	836	36	61	1607	140
16	10	10	206	60	10	185	38	6	442	89	27	1509	81	66	1647	94
17	10	11	118	36	11	232	83	7	218	81	30	1615	145	72	2392	249
18	7	15	154	41	17	349	145	12	349	196	39	353	232	83	2184	931

Appendix B5. Soil clay and fine silt contents determined by three techniques for 173 samples.

N	Technique						N	Technique					
	Pipette sampling Water-dispersed		**Hydrometer** Calgon-dispersed		**Laser analyser** Water-dispersed			**Pipette sampling** Water-dispersed		**Hydrometer** Calgon-dispersed		**Laser analyser** Water-dispersed	
	Clay	Fine silt	Clay	Fine silt	Clay	Fine silt		Clay	Fine silt	Clay	Fine silt	Clay	Fine silt
1	1.6	16.2	14.9	8.0	6.5	25.4	32	1.3	0.1	0.6	0.4	0.8	2.6
2	0.7	11.0	9.2	7.3	5.5	34.2	33	1.4	4.6	3.4	1.3	3.8	29.2
3	1.5	7.3	6.7	3.0	3.6	15.6	34	1.3	3.1	5.3	0.6	1.4	8.6
4	1.5	8.6	20.5	0.1	5.6	22.9	35	1.4	4.3	3.5	2.7	1.3	8.0
5	2.1	8.3	9.2	4.0	4.8	29.7	36	1.5	9.6	3.7	8.1	3.1	12.2
6	1.5	10.6	12.1	8.6	6.2	37.8	37	1.1	6.2	3.2	5.1	3.8	18.8
7	1.4	9.3	4.2	10.5	3.3	18.3	38	1.6	7.3	3.7	5.8	3.6	10.4
8	1.8	5.8	4.3	7.9	3.2	15.8	39	1.5	8.5	5.2	5.9	7.9	37.8
9	0.5	3.0	0.8	6.2	2.1	14.0	40	1.0	3.7	1.6	3.3	1.6	12.7
10	1.1	9.0	1.5	10.5	2.9	15.7	41	1.7	5.0	4.5	2.5	1.5	8.2
11	1.5	10.9	3.5	8.8	4.0	20.3	42	0.8	1.5	0.9	1.9	0.9	3.7
12	0.9	9.4	13.2	9.0	2.9	17.3	43	0.7	1.0	1.3	1.7	0.8	2.7
13	0.6	0.2	0.0	0.2	0.4	1.9	44	0.4	0.3	0.0	0.2	0.7	2.1
14	0.5	3.0	2.4	1.1	1.5	7.6	45	0.6	0.5	0.1	0.7	0.3	0.5
15	1.0	1.8	2.8	1.5	1.4	7.3	46	0.6	0.6	0.0	0.1	0.4	0.6
16	0.9	1.3	0.0	0.6	1.3	3.9	47	0.6	0.6	5.3	1.0	0.4	1.4
17	0.7	0.7	0.4	0.1	0.5	1.7	48	1.5	12.2	15.3	6.1	3.0	14.5
18	0.6	0.5	0.1	0.5	0.7	4.0	49	0.3	4.2	2.9	0.5	1.4	6.1
19	0.0	0.9	0.1	0.4	0.5	1.9	50	2.5	18.4	14.0	12.7	6.5	18.9
20	0.4	1.8	0.4	0.6	0.9	4.1	51	1.0	3.0	2.8	1.1	1.8	7.3
21	1.1	1.6	2.4	0.3	1.0	6.7	52	3.4	21.6	14.8	12.2	8.0	25.8
22	0.2	2.5	1.2	0.5	1.1	5.2	53	4.6	14.8	15.0	15.8	10.4	49.5
23	0.2	2.0	1.5	0.5	1.3	6.1	54	1.8	11.4	7.2	10.1	14.4	44.1
24	0.1	1.5	0.1	0.2	0.7	2.8	55	1.4	6.2	4.6	7.4	12.1	43.9
25	0.8	7.6	3.3	9.0	1.7	12.2	56	2.5	9.3	12.1	3.2	9.1	18.3
26	1.9	9.0	4.5	6.6	4.2	20.4	57	6.5	15.5	18.1	18.6	12.0	19.4
27	1.8	6.2	7.1	8.4	8.8	31.1	58	3.7	10.1	17.6	15.9	6.6	20.0
28	0.7	6.2	7.4	8.7	1.6	10.8	59	4.3	37.1	33.9	36.6	12.2	33.0
29	2.2	11.4	9.7	11.6	3.8	21.9	60	2.8	7.3	6.5	9.1	13.0	41.2
30	1.0	0.3	0.6	0.0	1.2	3.4	61	1.2	5.4	26.8	25.3	7.6	13.2
31	1.0	0.2	0.5	0.5	1.3	4.1	62	0.8	1.6	6.7	3.9	2.7	8.6

Appendix B5, page 2.

N	Technique						N	Technique					
	Pipette sampling Water-dispersed		**Hydrometer** Calgon-dispersed		**Laser analyser** Water-dispersed			**Pipette sampling** Water-dispersed		**Hydrometer** Calgon-dispersed		**Laser analyser** Water-dispersed	
	Clay	Fine silt	Clay	Fine silt	Clay	Fine silt		Clay	Fine silt	Clay	Fine silt	Clay	Fine silt
63	4.5	12.6	9.0	14.2	11.5	17.6	94	0.4	7.0	0.1	0.9	1.8	5.2
64	2.2	8.5	7.0	8.9	13.4	41.6	95	0.6	4.6	1.4	4.2	1.5	6.5
65	3.3	7.5	8.0	11.2	12.5	43.6	96	1.2	0.1	0.1	1.4	2.3	11.8
66	1.7	5.3	29.7	30.1	2.0	13.3	97	0.8	1.8	2.5	6.1	1.5	8.0
67	1.0	3.6	1.8	6.2	1.6	12.1	98	1.1	3.1	1.0	3.3	1.5	6.6
68	1.5	3.7	17.5	3.9	2.0	13.0	99	2.9	3.8	1.1	2.4	7.0	12.5
69	0.4	4.9	4.3	7.1	1.3	15.5	100	1.7	5.0	12.1	20.6	6.9	17.5
70	0.8	3.9	17.3	0.1	2.1	12.0	101	1.0	0.1	7.6	19.8	3.8	5.7
71	0.6	3.6	4.1	5.0	1.0	8.7	102	0.4	2.2	11.4	11.0	0.9	3.1
72	2.6	8.0	2.8	5.9	2.7	15.7	103	4.4	10.2	1.6	3.3	14.9	42.6
73	1.6	4.5	4.1	4.2	2.1	13.3	104	2.6	8.5	6.1	9.4	6.8	19.6
74	5.2	11.6	8.9	2.9	13.8	40.5	105	2.1	2.2	5.3	8.5	4.3	23.8
75	3.2	3.1	11.6	7.4	4.2	11.9	106	1.5	2.4	3.6	4.5	2.1	13.2
76	3.8	6.7	5.2	9.4	3.7	13.7	107	2.1	10.2	4.7	2.3	3.9	20.7
77	3.1	0.8	5.5	9.7	8.3	20.3	108	1.4	9.7	2.7	1.3	2.1	7.2
78	4.0	8.4	20.4	22.7	9.4	22.7	109	0.7	7.2	19.1	3.4	6.5	19.1
79	3.9	13.0	17.6	25.2	6.6	13.8	110	1.0	4.1	16.5	7.6	8.3	20.2
80	0.6	10.6	0.0	0.4	1.0	2.6	111	1.0	8.0	1.6	2.0	1.0	4.4
81	0.6	9.4	2.0	2.0	1.0	3.2	112	1.0	2.7	5.7	3.4	8.0	39.5
82	0.3	14.9	6.7	33.7	1.2	3.0	113	1.8	10.6	8.1	6.2	6.9	42.3
83	0.3	10.5	15.4	15.0	1.1	2.7	114	3.8	11.9	22.3	37.0	12.3	48.6
84	0.3	1.4	0.0	0.3	0.8	1.8	115	4.6	1.5	3.5	55.0	10.7	45.6
85	0.2	2.6	5.2	9.7	1.0	3.5	116	1.8	6.7	18.7	27.6	6.6	42.7
86	1.6	1.5	10.4	3.5	2.4	18.6	117	4.8	9.5	30.9	36.1	13.5	56.5
87	1.4	1.0	7.4	4.1	2.4	18.5	118	1.7	15.3	36.9	5.4	8.4	39.3
88	1.0	1.1	0.8	7.4	1.8	10.1	119	2.0	21.0	24.8	28.4	5.9	39.9
89	0.7	2.0	8.4	10.7	3.2	11.1	120	2.6	6.0	34.8	23.5	2.6	23.6
90	1.7	7.6	3.7	7.1	1.5	11.0	121	1.4	15.6	12.3	7.5	3.5	10.2
91	0.9	6.0	0.9	3.0	2.0	11.8	122	4.1	9.5	20.7	13.1	9.5	30.6
92	0.4	5.9	1.1	0.1	0.5	1.7	123	4.2	7.1	17.5	19.8	11.8	31.3
93	0.6	6.9	0.1	4.5	1.5	5.8	124	1.2	17.7	10.9	5.1	2.4	11.2

N	Technique						N	Technique					
	Pipette sampling Water-dispersed		**Hydrometer** Calgon-dispersed		**Laser analyser** Water-dispersed			**Pipette sampling** Water-dispersed		**Hydrometer** Calgon-dispersed		**Laser analyser** Water-dispersed	
	Clay	Fine silt	Clay	Fine silt	Clay	Fine silt		Clay	Fine silt	Clay	Fine silt	Clay	Fine silt
125	5.4	3.1	10.3	19.4	9.5	28.8	150	1.8	2.4	3.6	7.0	2.2	9.1
126	6.1	10.3	15.5	24.5	11.9	41.6	151	1.1	1.8	3.4	4.1	3.3	8.5
127	2.3	17.4	11.1	17.0	7.5	28.8	152	6.6	2.3	9.3	13.7	3.4	10.7
128	2.6	4.0	16.4	25.9	6.1	40.3	153	2.4	2.0	3.9	5.8	4.8	13.8
129	1.3	14.6	12.4	9.0	4.0	19.6	154	1.8	6.6	3.6	5.8	3.6	10.1
130	3.4	9.1	24.7	28.1	5.7	29.5	155	1.3	2.5	2.0	7.9	4.4	9.8
131	1.3	12.6	14.5	14.3	3.8	17.0	156	0.5	4.2	1.4	3.1	1.6	7.3
132	0.6	8.5	1.6	1.1	0.5	0.4	157	1.1	7.2	3.7	8.8	4.0	18.8
133	1.3	2.2	1.0	0.1	1.2	3.3	158	1.0	6.1	1.2	4.1	5.6	11.0
134	0.6	9.7	0.6	0.4	1.4	5.1	159	1.1	3.7	0.2	4.2	2.9	11.9
135	0.5	3.0	0.0	0.2	1.1	3.5	160	1.3	3.8	1.5	4.2	3.1	11.8
136	0.2	0.0	0.0	0.2	0.6	0.5	161	0.4	10.6	1.9	5.0	2.1	9.8
137	0.7	0.3	0.1	0.3	1.2	4.1	162	0.2	5.4	1.0	7.7	0.1	1.2
138	1.3	0.7	0.9	4.9	3.7	11.5	163	0.3	5.9	0.1	7.9	0.3	1.6
139	0.6	1.0	0.1	0.5	1.5	5.5	164	0.2	5.8	0.2	7.7	0.1	0.5
140	0.9	0.2	1.8	4.6	1.4	5.3	165	0.2	5.8	0.1	0.2	0.3	1.2
141	2.3	1.0	5.0	7.9	3.8	11.3	166	0.0	0.4	10.0	1.9	0.3	2.1
142	3.6	7.4	5.8	9.2	3.5	10.6	167	0.8	2.2	0.3	4.4	0.2	1.6
143	2.1	2.6	2.0	6.2	7.8	34.5	168	0.2	0.7	0.1	0.0	0.6	1.9
144	1.0	1.7	2.6	7.8	2.3	11.0	169	0.0	1.2	0.0	0.2	0.6	2.0
145	1.0	5.7	1.7	8.0	2.8	10.9	170	0.3	1.8	2.0	2.0	1.1	2.8
146	1.0	7.0	1.7	6.3	5.1	11.7	171	0.7	0.2	0.6	1.9	1.0	5.4
147	2.8	5.4	22.2	0.4	1.7	9.0	172	0.7	1.2	0.1	0.1	0.6	2.3
148	1.4	4.1	0.8	4.1	2.0	9.0	173	0.0	1.4	0.1	0.7	0.7	2.9
149	1.4	3.5	1.9	5.0	2.2	9.0							

Appendix B6. The quantile values (0.95 and 0.1) for the infiltrability data grouped into classes according to the contents of clay and fine silt fractions determined by three different techniques (laser analyser, hydrometer, and pipette sampling).

Class No.	Sample No.	Soil fractions content determined by three different techniques (μm)																	
		Laser analyser						Hydrometer						Pipette sampling					
		Clay			Fine silt			Clay			Fine silt			Clay			Fine silt		
		Fraction content Mean %	Infiltrability mm hr^{-1} quantile 0.95	0.1	Fraction content Mean %	Infiltrability mm hr^{-1} quantile 0.95	0.1	Fraction content Mean %	Infiltrability mm hr^{-1} quantile 0.95	0.1	Fraction content Mean %	Infiltrability mm hr^{-1} quantile 0.95	0.1	Fraction content Mean %	Infiltrability mm hr^{-1} quantile 0.95	0.1	Fraction content Mean %	Infiltrability mm hr^{-1} quantile 0.95	0.1
1	10	0.3	2591	277	1.0	2766	313	0.0	1856	279	0.1	1209	197	0.1	1680	257	0.2	2766	333
2	10	0.6	2188	523	1.9	1263	361	0.1	1207	73	0.3	1827	282	0.3	1827	104	0.6	1680	168
3	10	0.9	1340	159	2.8	1340	183	0.3	2591	119	0.5	881	161	0.4	1523	150	1.1	1105	183
4	10	1.1	434	232	3.8	889	170	0.8	596	80	0.8	1611	107	0.6	1839	92	1.6	764	162
5	10	1.3	748	117	5.4	352	101	1.2	1255	42	1.7	971	78	0.7	510	66	2.0	1131	109
6	10	1.5	334	89	7.0	554	88	1.6	1353	39	2.7	325	53	0.8	2127	63	2.4	1237	88
7	10	1.7	319	77	8.7	320	88	2.2	390	51	3.6	205	37	0.9	248	51	3.1	407	75
8	10	2.1	445	88	10.3	364	74	3.1	461	67	4.3	1841	86	1.1	748	44	3.8	275	52
9	10	2.4	159	43	11.3	145	50	3.7	142	28	5.2	203	26	1.2	238	67	4.7	226	71
10	10	3.0	126	39	12.2	213	45	4.4	206	43	6.1	239	64	1.3	631	51	5.7	166	46
11	10	3.6	364	40	13.8	166	63	5.5	267	50	7.2	370	43	1.5	590	69	6.4	166	28
12	10	3.9	243	66	16.9	180	31	7.0	262	42	7.9	1680	43	1.6	190	27	7.3	165	26
13	10	5.0	193	42	19.1	173	23	9.0	722	30	8.8	126	42	1.8	116	27	8.3	200	37
14	10	6.4	135	25	21.7	226	25	11.4	1175	37	9.8	185	40	2.2	108	27	9.3	90	22
15	10	7.6	116	43	29.0	186	37	14.5	208	30	12.9	1048	30	2.7	215	37	10.2	144	29
16	10	9.6	168	21	37.7	126	16	17.6	192	23	19.3	182	23	3.6	76	24	11.6	152	31
17	13	12.9	80	16	44.9	71	23	26.8	282	16	31.8	166	16	5.0	109	16	18.5	87	16

APPENDIX C: THE LATITUDE AND LONGITUDE COORDINATES OF THE BIOTA SOUTHERN AFRICA OBSERVATORIES SAMPLED IN THE PRESENT STUDY

N	Abbreviation	Name	Coordinates
1	M	Mile	18°24’15.1”S / 19°17’41.1”E
2	MU	Mutompo	18°18’06.4”S / 19°15’30.0”E
3	S	Sonop	19°04’58.3”S / 18°54’48.3”E
4	SM	Smalstreep	21°S / 16°E
5	O	Omatako	21°30’37.7”S / 16°43’45.2”E
6	E	Erichsfelde	21°35’48.7”S / 16°56’41.2”E
7	C	Claratal	22°77’98”S / 16°77’53”E
8	NAR	Narais	23°12’03”S / 16°89’65”E
9	D	Duruchaus	23°13’36”S / 16°90’04”E
10	W	Wlotzkasbaken	22°18’54.0”S / 14°28’09.1”E
11	GA	Ganab	23°12’22”S / 15°53’89”E
12	GO	Gobabeb	23°53’28”S / 15°04’73”E
13	R	Rooisand	23°29’49”S / 16°10’54”E
14	NR	Niko Reserve	25°34’25”S / 17°83’90”E
15	NG	Niko Grazing	25°33’34”S / 17°84’89”E
16	NA	Nabaos	26°23’26.3”S / 17°59’43.7”E
17	GE	Gellap Ost	26°24’04.2”S / 18°00’17.5”E
18	A	Alpha	26°45’39.3”S / 20°36’50.5”E
19	G	Gondwana	27°41’07.9”S / 17°48’05.3”E
20	K	Koeroegapvlakte	28°14’08.4”S / 17°01’32.4”E
21	N	Numees	28°18’07.6”S / 16°57’50.4”E
22	Y	Yellow Dune	28°61’23”S / 16°65’43”E
23	SN	Soebatsfontein	30°11’43.2”S / 17°33’13.6”E
24	PK	Paulshoek	30°23’41.1”S / 18°17’10.1”E
25	RH	Remhoogte	30°23’43.4”S / 18°17’32.5”E
26	GH	Goedehoop	31°17’08.6”S / 18°36’07.3”E
27	RG	Ratelgat	31°17’09.2”S / 18°36’01.3”E
28	MD	Moedverloren	31°27’39.5”S / 18°26’58.5”E
29	RL	Riverlands	33°29’21.6”S / 18°34’48.4”E
30	EB	Elandsberg	33°25’52.0”S / 19°01’50.5”E
31	CP	Cape Peninsula	34°16’09.2”S / 18°23’32.0”E