Pedodiversity of southern African drylands

Dissertation

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I Content

II Abbreviations and acronyms

AM-extractable	NH_4-acetate extractable
asl	Above sea level
BIOTA	Biodiversity Monitoring Transect in Africa
BSC	Biological soil crust
CC	Calcium carbonate
CEC	Cation Exchange Capacity
DEM	Digital elevation model
DGPS	Differential GPS
DOC	Dissolved organic carbon
$EC_{2.5}$	Electric conductivity in 1:2.5 solution
EC_5	Electric conductivity in 1:5 solution
EC_e	Electric conductivity in saturated paste
Fe_d	Dithionite soluble iron
Fe_o	Oxalate soluble iron
GEOSS	Global earth observation system of systems
GPS	Global position system
GTOS	Global terrestrial observing system
IGBP	International Geosphere–Biosphere Programme
INSPIRE	Infrastructure for spatial information in Europe
Mpa	Mega-Pascal
n.a.	Not analysed
OC	Organic carbon
OP	Osmotic potential
RS	Rooting space (%)
SET	Soil eco type
SRTM	Shuttle radar topography mission
TRB	Total reserve in bases ($cmol_c\ kg^{-1}$)
WRB	World Reference Base for Soil Resources

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To paraphrase Leonardo da Vinci:

'Why do we know more about distant celestial objects than we do about the ground beneath our feet?'

1 Thematic background and general aims

Soil is one of the most important non-renewable resources for humankind and forms a central part of our environment. Next to water, air and energy, the soil is an indispensable factor for environmental services such as biomass for food, fodder and renewable energy (biosphere) as well as filtering, buffering and transforming clean ground water and clean air (atmosphere and hydrosphere) (BLUM 2006). Whereas the consequences of global change for the atmosphere, hydrosphere and biosphere (especially biodiversity) have received increasing attention in politics, the general public and science over the past decades, the importance of the soil has only been little recognised to date, regardless of the central role it assumes in the interrelation of these spheres.

Soil as a central part of the environment and factor for biodiversity

Recently, the perception is shifting from pedosphere as an exclusive focus on substrate for food production and carbon sequestration in global change contexts (LAL 2004a, 2004b) to its fundamental ecological and biodiversity potential (WILDING & LIN 2006). LAL (2006) emphasises the need to study processes governing interaction between the pedosphere and the biosphere for enhancing agronomic and biomass productivity and improving the understanding of biodiversity. Numerous statements highlight this change in perception by stressing that biodiversity is an important research field with regard to future perspectives of soil science (HARTEMINK 2006).

This study contributes to the understanding of soil diversity (pedodiversity) and its significance for the ecosystem. The introduction leads the reader into the fields of biodiversity and its relation to the abiotic environment and highlights the research needs in geo- and pedodiversity. A brief outline of the BIOTA Southern Africa project explains the research background and infrastructure, and subsequently the overarching aims of this study are introduced. The basic concepts of bio-, geo- and pedodiversity are reviewed in more detail in chapter 5 of this thesis.

1.1 Understanding biodiversity in a global change context

Biodiversity is much more complex than mere species numbers

Biodiversity assumes a pivotal role for sustaining human existence on earth (UNEP 1992). Over recent years, it has received increasing attention in the scientific, political and public sphere. Currently, biodiversity is subject to tremendous change, mainly manifested in the loss of species, which is the most public biodiversity issue. More complex, but not raised by the media, is the importance of understanding the processes and of maintaining biodiversity and ecosystem functions sustainably (UNEP 2007). In order to achieve this aim, all elements of biodiversity need to be preserved on different natural levels, ranging from the genetic and species scales to ecosystem and landscape scales while also considering their abiotic drivers (HEYWOOD 1995). The international Convention on Biodiversity (CBD), which was implemented in the year 1994, acknowledged this for the first time on a global level. In Article 2, it defines the term biodiversity, reading far beyond the common understanding of biodiversity as species richness in flora and fauna:

> "*Biological diversity means the variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems*" (UNEP 1992)

Humans extensively influence biodiversity

Humans have extensively altered these ecosystems globally on various levels, e.g. by changing global biochemical cycles, transforming land and enhancing the mobility of biota. Together with natural phenomena, these changes have altered the biological diversity of the earth. Due to its major impact, CRUTZEN (2002) recommended the term "Anthropocene" for this new geologic epoch in which humankind significantly reshapes the face of the planet. With respect to biodiversity, this is expressed by changes of species composition, elimination of species in areas of direct human influence, or even extinction of species. Although extinction is a natural process, the human alteration of the global environment has triggered the sixth major extinction event in the history of life and caused changes in the global distribution of species (CHAPIN et al. 2000). This is due to both, a direct impact resulting from urbanisation and agriculture and – indirectly - the change of the environment as recently raised in the global change discussion (e.g. BOTKIN et al. 2007, WALTHER et al. 2007). The latest IPCC report 2007 clearly declared that the world is warming up and that humans are to a major extent responsible (KERR 2007).

The effects of climate change are not evenly distributed, but a variable magnitude of influences in different regions of the earth can be observed. SALA et al. (2000b) assume the greatest change in biodiversity within this century for the Mediterranean climate and grassland ecosystems due to their sensitivity for even small changes in temperature and precipitation (see also THUILLER 2007). Moreover, the focal region of this study, southern Africa, is expected to be one of the regions experiencing the strongest changes worldwide with strong reductions on rain-fed agriculture yields and considerably increase of arid and semi-arid land (see also SCHOLES et al. 2006, IPCC 2007).

Drylands are strongly affected by climate change

The region of southern Africa includes several hotspots of biodiversity (MYERS et al. 2000, KÜPER et al. 2004, BROOKS et al. 2006), such as the Southern African Cape Region and the Namibian centres of endemism which are expected to suffer intensely from climate change (www.biota-africa.org, see also KIER & BARTHLOTT 2001, MIDGLEY et al. 2002a, THOMAS et al. 2005, SCHOLES & BIGGS 2005, THUILLER et al. 2006a, 2006b). In particular, the UNESCO report on climate change and world heritage (2007) noted a threat for the UNESCO Heritage site Cape Floral Region caused by climate change leading to shrinkage of bioclimatic habitats due to warming and changes in precipitation.

The awareness of the above listed problems and the focus on biodiversity within political, cultural and biological discussions was raised mainly during the last decade. Dryland research increasingly becomes an important issue in scientific debates as well as in practical, political and humanitarian topics. However, the prediction and even more the prevention of changes in biodiversity are very complex, as many processes and drivers are not yet understood. Remarkably little is known about the essentials of biodiversity, i.e. the mechanisms controlling the species richness of ecosystems (POREMBSKI & BARTHLOTT 2000). Therefore, the relationship between biodiversity and ecosystem functioning has emerged as a central issue in ecological and environmental sciences during the last decade (LOREAU et al. 2001). Still, many processes are not yet understood and next to numerous studies of single disciplines, a more holistic research approach is urgently required in order to account for and synthesise the relevant fields of biotic and abiotic influences on biodiversity.

Already at the beginning of modern ecology research, Alexander von Humboldt (1769 – 1859) used such holistic approaches with his analysis of the “Entirety of a landscape” (see ‘Kosmos’, von HUMBOLDT 2004). Today, LESER and NAGEL (2001) observed increasing tendencies to split such holistic approaches into more mono-disciplinary approaches during the second half of the last century. They recommend to intensify studies on geodiversity and biodiversity with regard to the spatial dimension and to focus on transdisciplinary research with holistic approaches, as this forms a prerequisite for the development of sustainable concepts in the use of biodiversity. PHILLIPS and MILLER (2002) stated in this context:

A holistic understanding of ecosystems is of paramount importance for sustainability

> *'The more we know about how diversity is distributed and* *__controlled__* *spatially, the more effectively the scientists will be able to provide the information needed to manage the planet's biotic resources*.'

The complicated patterns and functions of ecosystems become obvious when biodiversity is set in relation to its underlying environmental factors. One has to distinguish between effects of the abiotic and biotic environment on different scales and long-term evolutionary effects, which can be summarised as historical factors (e.g. vegetation history, paleoclimate, paleogeography). On a macro scale, the combination of temperature and precipitation regime is supposed to be the main driving factor for the differentiation of biomes (RICKLEFS & MILLER 2000). This relationship is additionally affected by different evolutionary time periods and nowadays strongly modified by human impact. The same is true for the principal pattern of an increase in species richness from the pole to the equator (RICHTER 2001). Many authors have observed such an increase in species diversity with decreasing latitude, proposing a variety of explanations (for an overview see HAWKINS et al. 2003 and DAVIES et al. 2004). However, for instance the biodiversity hotspot Fynbos in South Africa does not confirm these overall trends. Recent compilations of the Earth's phytodiversity provide comprehensive information about the distribution of diversity (KIER et al. 2005, BARTHLOTT et al. 2005, MUTKE & BARTHLOTT 2005, KREFT et al. 2006). Advanced GIS techniques and improved data availability further enhance the inclusion of additional data such as topography or rough soil type distribution (FERRIER et al. 2004). Highly geodiverse areas such as mountainous regions in the tropics and subtropics coincide with centres of vascular plant diversity (MUTKE & BARTHLOTT 2005). They have to be considered as special situations as they include strong environmental gradients over short distances resembling different biomes. This effect of geodiversity is shown for example by the Andes, which are marked as a global hotspot of biodiversity. The diversity of the physical environment favours both, evolutionary ecological specialisation and complex landscapes with high actual habitat diversity (BARTHLOTT et al. 2005). A study focusing on southern Africa THUILLER et al. (2006) also mentions topodiversity as one of the most important drivers for plant species richness.

Phytodiversity and geodiversity on a macro scale

Regional environmental heterogeneity and the need for methodology

Reducing the scale to the regional or local level, the distribution of species and population is regarded as strongly affected by abiotic factors such as topography and soils (RICKLEFS & MILLER 2000). On these scales, abiotic environmental heterogeneity is assumed the most important driver for species richness and patterns besides population interaction (GASTON 1996). The assumption is not a new one, there are numerous studies proving the relationship between the abiotic and biotic environment. Often, diversity patterns are very obvious and can be described exactly, while their causal factors usually remain obscure. PHILLIPS & MILLER (2002) see one primary reason in the failure of an effective sampling of the world's diversity with standardised methods. Only few of the available studies used standardised methods allowing comparability of the results. One rare example is Alwyn Gentry, who began in the early 1970s already with studies designed for the comparison of diversity of tropical forests (see CLINEBELL et al. 1995). GENTRY applied standardised transect walks for determining the tree diversity on 0.1 ha sites. Despite the simplicity and the descriptive character of Gentry's data, such an extensive set of comparable data had never been collected before on a worldwide scale (PHILLIPS & MILLER 2002). Formulating research needs for the Millenium Ecosystem assessment, CARPENTER et al. (2006) stated:

> *'The research community needs to develop analytical tools for projecting future trends and evaluating the success of interventions as well as indicators to monitor biological, physical, and social changes.'*

The increasing awareness regarding the importance of standardised methodologies and the exchange of observation data recently led to the establishment of information networks such as GEOSS, incorporating activities of e.g. GTOS and DIVERSITAS on an international level or INSPIRE on a European level.

Next to methodological problems such as standardisation of data in biodiversity studies, the lack of methods to qualify complex abiotic environments remains a major problem in research. The spatial abiotic heterogeneity is often cited as a factor that strongly affects biotic diversity (e.g. HUSTON 1994, ROSENZWEIG 1995, HUTCHINGS et al. 2001), while integral quantifications of these factors are rarely performed.

Pedodiversity: a recent concept

Soil represents the critical interface between atmosphere, lithosphere, biosphere and hydrosphere, and it is thus an ideal integrative component reflecting the variety of influences. Moreover, it is the most important resource for biotic components (YAALON 2000). Integrative approaches quantifying soil diversity, so-called pedodiversity analyses, are a recent field of scientific interest. They deal with integrative indices of soil variability and are reviewed in detail in chapter 5 of this thesis. The concepts and tools were mainly introduced by IBANEZ et al. (1990, 1995, 1998). Several studies with contributions that addressed theory, methodologies and applications were conducted and published subsequently. MCBRATNEY (1992) defined pedodiversity in a simple overarching approach as

'*the variation of soil properties or soil classes within an area*'.

Understanding and maintenance of ecosystem functions are the primary purposes of pedodiversity studies, which use relatively new techniques for the assessment of the variability of soils. It is expected that pedodiversity will become an important index of soil quality of an area and that its estimation will become an integral part of soil-resource assessment (MCBRATNEY et al. 2000). The collective metabolic and growth activities of the earth biota move large amounts of elements and compounds between the hydrosphere, atmosphere and lithosphere every year (NAEEM 2002). In terrestrial ecosystems, the soil is nearly always directly or indirectly involved or affected by these processes and is therefore key to understanding biodiversity. PHILLIPS (1999) stated:

> *„Increases or decreases in the diversity of any environmental component are likely to be accompanied by similar changes in the other components. This confirms the practise of conserving biodiversity by protecting and enhancing habitat diversity. It also implies that the loss of biodiversity will have broader environmental repercussions."*

Pedodiversity as an integrative factor for environmental heterogeneity

The importance of pedo- (and geo-) diversity (often included in habitat diversity) for biodiversity has long been acknowledged in ecological research (e.g. JENNY 1941), and recent studies have recognised the link between biodiversity and pedodiversity methods (e.g. GUO et al. 2003). However, few studies have used pedodiversity as a supplementary tool for biodiversity analyses in order to measure or even quantify pedodiversity and relate this to biodiversity studies. As IBANEZ et al. (1995) stated:

> *"The diversity of soils and land forms has hardly received the attention of researchers. This is surprising since variation in these have profound qualitative and quantitative repercussions on the landscapes. The characterisation and quantification of diversity of landform, rock and soil as non-renewable natural resources should be taken into account when estimating a territory's ecological value"*

Figure 1 shows the basic scheme of the mutual dependency between biodiversity and pedodiversity, the latter of which can be regarded as the most comprehensive abiotic factor. The different definitions (parametric, taxonomic, etc.) demonstrate that the term cannot be defined exactly and depends on the study objectives and methods. This study focuses on the taxonomic and parametric pedodiversity and corresponding quantification tools.

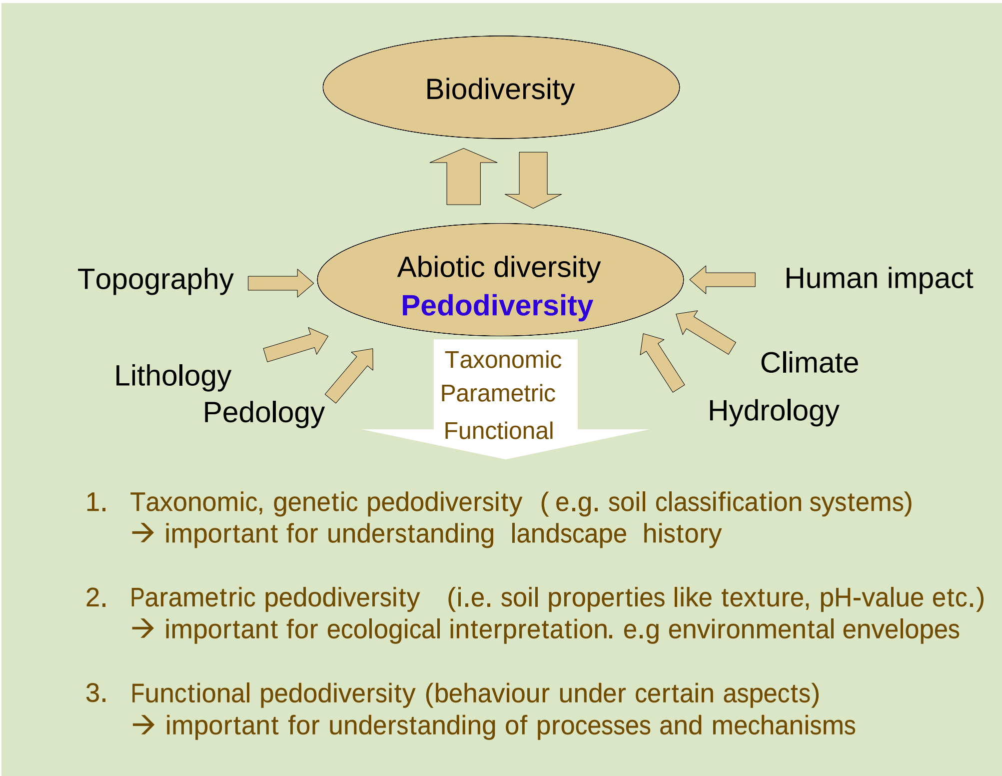


Figure 1 Pedodiversity as an integrative parameter for abiotic diversity

The theoretical concept of pedodiversity has been discussed in the soil science community and is reviewed in this thesis. While the concept emphasises in most cases the taxonomic diversity of a soilscape, much less attention has been paid to the parametric and functional aspects of pedodiversity. This study aims to provide a contribution in the quantification of pedodiversity and its importance for biodiversity by the use of standardised data collected within the BIOTA Southern Africa project. The integrated research approach of this interdisciplinary project provides one of the rare opportunities to use standardised data of different disciplines for the methodological development and validation of pedodiversity quantification.

1.2 The BIOTA Southern Africa project

The work presented here is part of the “BIOTA Southern Africa” project (Biodiversity Monitoring Transect Analysis in Africa), which belongs to the BIOLOG framework programme funded by the German Federal Ministry of Education and Research (BMBF) (see also www.biota-africa.org). The BIOTA AFRICA network includes numerous African and German research projects using a joint interdisciplinary and integrative approach to analyse the changes of biodiversity on the African continent. The goal of BIOTA Southern Africa, in particular, is to gain knowledge for decision makers for a feasible and sustainable management of biodiversity, by taking natural, as well as socio-economic conditions, into account. To this end, the knowledge of anthropogenic, biotic and abiotic drivers and processes is an inevitable prerequisite. In order to understand the changes of biodiversity it is necessary to understand the rules and dynamics of the processes that take place. These process analyses are an indispensable requirement for modelling approaches in order to predict and analyse climatic and land-use scenarios in an advanced stage of the project.

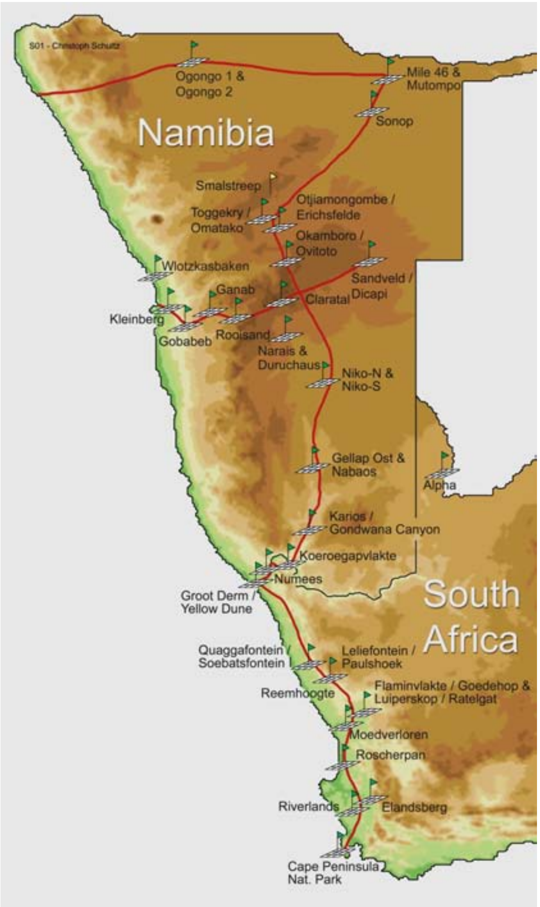


Figure 2 BIOTA Southern Africa transect with observatory locations

The interdisciplinary and applied research project concentrates on studies in Namibia and the western parts of the Republic of South Africa (RSA). Here, the BIOTA Southern Africa northsouth oriented transect with its eastwest-expanding side branches cover the most important climatic gradient of the subcontinent, following the rainfall gradient from the dry forests in Northern Namibia to semi-arid and arid savannas and further to the winter rainfall zones of the Cape Region in South Africa. Investigations are conducted along the entire transect of 2,000 km northsouth extension and concentrate on 35 standardised so-called ‘Biodiversity Observatories’ in the different biomes. These permanent monitoring sites of 1 km^2 size cover different land use types, rainfall gradients and important biomes. The observatories are (a) place-specific (b) joint research sites, investigated with (c) standardised methods, (d) standardised spatial and temporal scales, and (e) arranged in a network, which allows meaningful comparison, validation, extrapolation, and long-term monitoring and change detection (SCHMIEDEL & JÜRGENS 2005).

Within the BIOTA Southern Africa project, the soil science related subproject **”Edaphical diversity and biodiversity in mutual dependence”** focuses on the soil as important environmental factor strongly interrelated with biodiversity. One central part of this subproject is the assessment and analysis of the variability of selected abiotic properties on the biodiversity observatories along the BIOTA Southern Africa transect with a specially designed procedure (see chapter 2). By this, the importance of the abiotic parameters for the occurrence of various organisms and the biodiversity itself are analysed for southern African drylands. Here, the term ‘drylands’ incorporates a range of moisture regimes characterised by potential evapotranspiration, exceeding precipitation and markedly seasonal rainfall occurrence.

1.3 Aims of this study

As a part of the BIOTA Soil Science subproject, this study aims at an analysis of the pedodiversity of the selected southern African drylands and its relevance for biodiversity.

A lot of soil information across different scales is available for the broader study region of BIOTA Southern Africa, while an assessment of pedodiversity with standardised methods has not been established so far. Thus, the first major aim of this study was to close the gap of knowledge regarding the distribution and pattern of soils on both, a habitat orientated local scale (< 10 m – 1000 m <) by survey of the observatories as well as on a sub-continental scale by the transect analyses (100 km – 2000 km).

In order to apply a comprehensive approach for the quantification of the abiotic diversity, the second major aim of this study focuses on pedodiversity and its quantification. The development of criteria for pedodiversity and the relation of parameter-orientated pedodiversity indices to biodiversity will provide a future tool to quantify the relationship between pedo- and e.g. phytodiversity and will help to discriminate between the influence of soil and other factors (e.g. climate or evolution). At the same time, it provides a new possibility to quantify and compare the complexity of abiotic landscape structures and provides integrative attributes for planning purposes and for the evaluation of soil heterogeneity as an important characterisation of ecosystems.

In Figure 3, the major structural elements of this study are illustrated. The major aims and focuses can be summarised as the generation of a comprehensive soil database for pedodiversity analyses along the transect with respect to regional soil inventories and soil properties for local pattern analyses of 22 selected observatories. Only by a standardised data set, the development and application of different approaches for pedodiversity analyses is enabled and will support the understanding of ecosystem diversity. Moreover, it is an important contribution to the ongoing debate about possibilities and constraints of geo- and pedodiversity analyses.

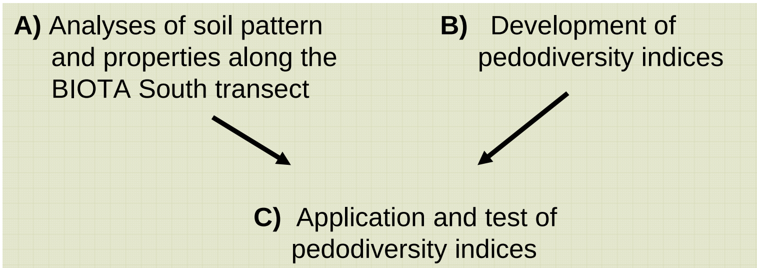


Figure 3 Major research fields and structural elements of this study

Each structural task comprises a number of methodological steps and questions that are followed up in this study:

A) <u>Analyses of soil pattern and properties along Biota South transect</u>

The objective of this task is to develop and apply suitable, standardised methods to describe soil variability and to generate a basic ecological understanding

- of all selected areas,
- with the same number of profiles,
- with identical laboratory data set,
- with a consistent classification of soil types and
- with parameters mostly relevant for plant occurrence and distribution.

B) <u>Development of pedodiversity indices</u>

Within this topic, the study aims at the development of pedodiversity indices

- based on current approaches in (geo-) pedodiversity,
- applicable to the data-set of task A for areas of 1 km^2 size ,
- using taxonomic as well as parametric soil properties,
- with a strong correlation to phytodiversity data and
- based on a comprehensive ecological understanding derived in task A.

C) Application and optimisation of pedodiversity indices

The different pedodiversity indices of task B have to be applied to the data set of 22 observatories. Based on own criteria this tasks aims at an optimisation of the pedodiversity indices with regard to data requirements, significance and correlation to phytodiversity.

The optimised analysis of pedodiversity along the southern African transect can be interpreted from numerous perspectives, the focus of this thesis is on the methodological comparison and the correlation analyses with phytodiversity data.

The thesis is structured in the way that first a detailed introduction is given on the basic sampling scheme and its development, including background information on various sampling strategies (chapter 2). Furthermore, methodological aspects of soil sampling, lab analyses and data processing are provided in this chapter. Chapter 3 builds the central part of soil analyses and soil information along the transect, including 22 observatories with a total number of 560 soil profiles. Each observatory is described with a regional overview, site characteristics and a detailed analysis of the soil situation and ecological aspects. Reference profiles and soil maps provide detailed insights into the main soil units resulting subsequently in an overview of the entire transect results (chapter 4).

Chapter 5 introduces the concepts of biodiversity and pedodiversity with a detailed review of the methods and developments in the fields of biotic and abiotic diversity assessment. It also introduces the term pedodiversity in detail. In chapter 6, three different approaches of pedodiversity analyses are introduced and applied. The development of two new parametric approaches is described in detail. Each approach is applied to the data set gathered in this study including a discussion of the results. Furthermore, the topics topodiversity, soil unit area curves and correlation to phytodiversity are analysed. Subsequent to this, an overall discussion of the pedodiversity analyses is included in chapter 7. Besides remarks on the data requirement of such analyses, here a comparison of the sensitivity of the different approaches and the suitability for phytodiversity analyses is given. Finally, overall conclusions and perspectives for future pedodiversity research are summarised.

2 Methods applied

This chapter comprises the description of the requirements and the development of the sampling scheme and the documentation of the applied field-, laboratory-, and classification methods.

2.1 Sampling scheme

The sampling scheme is one of the fundamental tools for the standardised assessment and monitoring of diversity. During an internal international workshop on methodology at the beginning of the project, disciplinary and interdisciplinary problems were highlighted and solutions discussed. With respect to the discussions, the resulting sampling procedure was mainly designed within the Soil Science working group. Thus, a detailed description of this sampling procedure and its development is provided in this chapter.

In any field study, the choice of the most appropriate sampling method is determined by the particular questions asked and the logistical constraints on the research. A vast number of sampling methods are used, most of them specialised to a certain discipline or objects of study. However, there are some basic requirements and principles, which are applied both in soil science and in phytobiology or phytogeography. It is not indented to explain all available methods here, but to provide a brief description of the most important parts that are used in the applied sampling procedure.

Empirical pattern analysis has provided most of the current knowledge regarding the structure and functions of soils. The early work of e.g. JENNY (1941), across large-scale regional gradients, had a substantial influence on the foundations of soil science and ecosystem ecology. The relationships generated from pattern analyses not only contribute to our knowledge of the structure, functions and processes of the soil, but also provide important predictive equations (SALA et al. 2000a).

For the BIOTA project, the monitoring aspects and the functional analyses are the main prerequisites to be considered in the sampling design for the regarded ecosystems, which are only partly understood in their function and dynamics. Moreover, the derived data should be suitable for extrapolation processes on the landscape scale. In interdisciplinary approaches such as the BIOTA project, the syntheses of the disciplinary results are also an important factor to deal with early in the starting phase of the sampling design.

The major task in the beginning of this project was therefore the development of a standardised and generally applicable investigation procedure to generate the most comparable and interdisciplinary database for the questions to answer. For diversity studies, this is the most important pre-condition. With respect to highlighting the background of the development of the sampling procedure, the next chapter gives a brief overview of the different approaches and their advantages and disadvantages applied in ecology and soil science.

2.1.1 Overview of sampling strategies in landscape ecology

The strategy for sampling must avoid bias and allow for replication to ensure the application of statistical analyses. General recommendations regarding the field of replication are given in HURLBERT (1984) and EBERHARDT & THOMAS (1991). Both, the sampling design and the details to be recorded are governed mainly by the purpose of the survey. This also has to consider the available resources and the desired accuracy and precision.

First of all, two general statistical approaches to sampling can be distinguished. The first one is the design-based approach using classical sampling theory, which has been used in many fields of ecology studies, including soil survey, during the last decades (e.g. HOWARD & MITCHEL 1985, WEBSTER & OLIVER 1990). The basic principle in this classical sampling theory is to define a target population comprising a set of units. In environmental survey, a population is almost always circumscribed by the boundary of a physical region and the units are all the places within it at which one might measure its properties. However, criticism against the application of this classical sampling theory and the calculating of statistical values in earth sciences arose, because these methods assume data as independent. BARNES (1988) stated:

> *"the classic development of nonparametric tolerance intervals begins with an assumption of independent, identically distributed random variables. This is unrealistic for the geologic environment – in general, geologic site characterisation data are not independent."*

As a result of such publications, many soil scientists seem to have abandoned the classical statistics and switched to a model based approach, which is using geostatistics (BRUS & DE GRUIJTER 1997). Whereas the classical theory approach mainly deals with "how much", the major strength of the model-based approach is in the determining "where" given soil properties are present (DOMBURG et al. 1994). Originally, the lack of detailed information about soil properties caused by the broadness of the existing classification systems led to this development of numerical and statistical methods for a more objective description of soil and its properties (e.g. WEBSTER & OLIVER 1990, 2001, PHILIPPS 2001, MULLA & MCBRATNEY 2000). The roots of these geostatistical methods are in the mining exploration to quantify and localise ore distribution. However, geostatistical approaches require high sampling effort and, if no basic information on the spatial dependence of studied parameters is available, pre-studies to adapt a reliable sampling design are necessary.

The discussion of these strategies was highly important in the beginning of the setup of the BIOTA sampling design to clarify the main goals of the design and the possibilities and restrictions of the different strategies for the disciplines. Thus, the sampling design of this project was developed with consideration of both, the interdisciplinary approach and the basic requirements of different sampling strategies. Due to the wide array of parameters studied, the geostatistical approach had to be reduced to basic requirements for simple interpolation techniques. As the resulting sampling scheme within the BIOTA project is a combination of different strategies, a brief introduction to these sampling strategies is provided (based on WEBSTER & OLIVER 1990, MULLA & MCBRATNEY 2000, HOWARD & MITCHEL 1985).

1. *subjective:* This strategy, also called purposive sampling, seeks to identify and to collect data within typical sample sites that is considered representative of distinct landscape units and identified by existing maps or other spatial structure information or by the investigator in the field. Depending on the existing knowledge of the system and the knowledge of the investigator, this technique can be highly effective. However, the major disadvantage is that the selection remains subjective and therefore statistically incorrect.
2. *random:* A relatively simple sampling approach to obtain statistically correct data is random sampling. Coordinates are chosen randomly out of the total population. This has the major advantage that each individual or site from the population has a known chance of appearing in the sample. However, uneven coverage of the sampling points often makes random sampling inefficient and time consuming, because some sampling points may cluster whereas other areas are by comparison sparsely sampled.
3. *systematic:* Evenly distributed sampling points or areas can be obtained by systematic sampling, in which sampling points are located at regular intervals on a grid. The location of the sampling points is very easy in this regular system, which is ideally aligned with the existing map grids. One has to be careful with periodicities in the investigated system, which can coincide with period of the grid (e.g. linear dune systems). However, the period of variation and its direction are in most cases detectable in advance and a grid can be chosen with unrelated spacing and orientation. The main disadvantage of systematic sampling is that classical probability theory is based on random selection and therefore the determination of the variance or standard error from the samples is no longer valid, because once one sampling point has been chosen (even in a grid) there is no randomization (WEBSTER & OLIVER 2001). In practise, as it is often expensive or time consuming to locate random plots in the field, systematic sampling may be preferred. HOWARD and MITCHELL (1985) suggested that systematic sampling will provide as good or even sometimes a better estimate of the mean for a specified number of samples than random sampling.

4. *stratified* (systematic or random): this type of design utilises prior information about the system and stratifies it in advance to capture the major variation of the area. The purpose of stratification is to reduce the variation within a given area and to increase the variation between strata by dividing the landscape, as observed on maps, aerial photographs, remote sensing data or in the field, into more homogenous classes. Stratification may be viewed as giving a reliability similar to unstratified sampling but with fewer samples (HOWARD & MITCHELL 1985). The stratification requires an a priori discrete classification of landscape types or habitats. Decisions made at this point may influence overall results and have to be taken carefully. Four basic types of a priori stratification are usually differentiated: i) by vegetation type, ii) by soil type, since soils integrate many of the ecosphere processes, iii) geomorphology as different slope positions and expositions, and iv) land-use units. Once the classification system is chosen, investigators generally select replicates by a standard field-sampling program within the units. Special care is required with regard to the interpretation of the results, since the units are chosen subjectively and only represent the investigator's point of view for stratification. Depending on the spatial structure of the regarded parameter, the units may have to be grouped again into new classes. Therefore, the stratification is just a tool to cover all obvious units at the beginning of the research. Stratification is not a sampling strategy itself, but has to be combined with random or systematic sampling within the strata.

5. *cluster:* The clustered sampling technique is recommended if a group of (micro-) habitats provides a more or less fixed pattern in relation to each other and the group as a unit provides part of another pattern formed by higher level units. Each group of microhabitats can be regarded as a cluster to be sampled. As the system as a whole consists of this cluster, the cluster technique would be sufficient to describe the structure of the landscape.

6. *transects* (combined with random, systematic or subjective point location): Transect sampling, or in soil science sampling a catena, is in very common use as a very efficient technique to cover a high number a different habitats with a simple sampling line. It works perfectly within landscapes with a linear structure or geomorphological sequences. However, without replication, single samples along a transect line are not adaptable for statistical analyses.

7. *geostatistical approach*: Whereas the classical sampling theory describes a population by means, variances and other statistical parameters, the geostatistical approach was developed for the regionalisation of the information (Theory of the regionalised variables, e.g. MATHERON 1971). The development of this *spatial statistics* originates largely from the mining sector. It arose from the need to improve the estimates of ore concentrations in rock and of recoverable reserves from fragmentary information. It provides the basis for describing variation on the earth surface, for estimating its

attributes precisely and for designing efficient sampling schemes (WEBSTER & OLIVER 1990). The procedure for a geostatistical sampling is split in two steps. In a first step, the spatial variation of the parameters to be investigated must be known. This is normally done by creating a variogram with field data (e.g. from a nested sampling). In a second step, the sampling scheme is created using the variogram information. This is normally a regular grid with a mesh size that considers the spatial variation of the investigated parameters. The term of efficiency in the context of sampling designs depends on the questions to answer. The described methods are the best techniques for a reliable description of the spatial distribution of selected parameters. However, this sampling requires much effort as information about the spatial variation must be known before and a systematic sampling grid with probably small-scale meshes has to be sampled completely. A further problem in more complex ecosystem analyses is that a wide range of parameters shall be investigated and each of them may vary in its spatial distribution. This is already the case for the soil and its different parameter. Even more complicated is the situation in interdisciplinary approaches where the set of parameters is broadened.

Tab. 1 Overview of sampling strategies and their advantages and disadvantages

Sampling-strategy	Advantage	Disadvantages
Subjective	• Specific selection of the plots to be sampled • Combined with expertise knowledge very efficient	• Statistically incorrect
Systematic	• simply discoverable points • statistically correctly, if total area = population	• variations smaller than grid spacing not enters • periodic variations can match with the grid spacing
Random	• statistically correctly, if total area = population	• lost of obvious variations • difficult location of the points
Stratified	• entry of the obvious Subunits • statistically correct within the subunits	• Subunits remains subjectively (invisible units, former use boundaries, sliding transitions) • difficult location of the points. • Border effects (more sites along border lines)
Cluster	• Entry of small scale variations	• Structure of the sampled population must be homogenous to capture all varieties of the given total area
Transect	• Efficient for linear structures or sequences	• Only linear spatial information
Geostatistical sampling	• best interpolation by kriging (spatial distribution)	• variogram must be known, otherwise complex transect analysis is presupposed

2.1.2 Development of the sampling procedure in the BIOTA project

The development of the standardised sampling procedure within the BIOTA project is presented in different steps. The established standards refer to the measurements and total size of the local investigation sites (observatories) as well as to the recommendations regarding distribution and concentration of research activities:

1. Setting the requirements for the methodology;
2. Implementation of the methodology;
3. Selection of biomes and land-use areas;

1. Setup of requirements for the methodology

> *Standardisation of the sample selection and the sample size is highly important in diversity studies as two samples of different sizes, drawn from the same assemblage can lead to quite different conclusions about its richness and diversity* (PIELOU 1975).

In fact, a frequent problem in interdisciplinary ecological studies is that the results of the different disciplines are often processed at different sites or different scales within a study area. To avoid these problems, the methodology within the BIOTA observatories should follow the optimum compromise between the discipline-specific investigation approach and the best aggregation of the different disciplines to achieve not only a characterisation of the sites but also the possibility to generate causality analyses from the results. To avoid a number of known problems, several requirements for the development of the sampling scheme, the "ranking procedure", were set:

- The selection of the sampling points should be non-subjective (randomised selection)
- Representative capture of inventory: Even with a low number of samples (< 10) the range of different strata shall be captured
- The resulting data shall be adaptable for extrapolation
- Interdisciplinary concentration: A maximum concentration of all subprojects on selected research sites to achieve a maximum of interdisciplinary approaches and interpretation of data, even with different sampling intensities → obligatory ranking of priority.
- Monitoring: The sampling site and technique should be structured for replicable sampling (Monitoring of exactly marked sites)

- Equal sized research sites along the entire transect (1 x1 km) representing the population for selection processes
- Northsouth and eastwest orientated border lines
- Subdivision of the total population (the square kilometre) in discrete units by a raster grid, i.e. in 100 sites of 100*100 m
- Stratification of the discrete units with respect to the obvious variations in the observatory. Consideration of the various landscape units (habitats) within the observatory, i.e. stratification of the square kilometre by clearly detectable variations. The kind and number of strata are not strictly predefined and should be selected by variations such as vegetation structure, morphology, land-use units or obvious soil variations. The main reason behind the stratification is not to describe the different strata by a number of samples but to capture the obvious variations within the observatory to ensure their implementation in the sampling procedure. Within a simple random approach this would not be possible

2. Implementation of the methodology

After establishing the framework mentioned above, the implementation of the sampling scheme was conducted by setting the standards, scales and programming the calculation procedure for the scheme

- The number of 100 hectares on each observatory are identified by numbers from 00 – 99, labelling starts in the NW corner of the observatory and is running to from west to east and north to south through the observatory
- Calculation of the centre co-ordinates for each hectare site as a starting point for the within hectare sampling scheme
- Determination of the division of the 1 hectare sites in various sampling points and monitoring areas to cover the needs of all subprojects and to avoid mutual disturbances
- Determination of an obligate ranking procedure for all 100 hectares within each observatory. Here, a proportionally higher consideration of rare landscape units (with a lower percentage of cover) for the higher ranked and primarily to be assessed sites aims at a representation of all landscape units. This ranking can be understood as a running representative selection of the different strata. This was necessary as due to the different scales of sampling and working intensities of the disciplinary assessments, the number of sampled hectares per observatory vary strongly among the different

subprojects. This sequence of priority is obligatory for all subprojects and ensures the highest achievable focus on the same series of hectares per observatory (calculation is explained in the following). The chosen d’Hondt procedure governs here the sequence of strata in the priority list, while a random selection determined the sites within the strata.

Explanation of the obligate ranking procedure using the d’Hondt method:

The principal item of the ranking of the randomised and stratified sampling sites (hectares) is a modified divisor method. Main purpose of the divisor methods is to create the allocation scheme of seats to parties in the electoral system, which is a basis of democracy.

One of the most used is the d’Hondt (introduced in 1878) method. Divisor rules used for proportional representation, such as d'Hondt are used to generate a sequencing procedure that determines exactly which party (here stratum) gets first, second, third, etc. choice of seats etc. (O'LEARY et al. 2005). Further references regarding the function of this method are TAAGEPERA (1989), BALINSKI & RAMIREZ (1999) and PALOMARES & RAMIREZ (2003).

A given number of sites to be sampled and the need to prioritise them into a ranking list is a problem, which can be solved by applying such a divisor method. We regard the inventory of the observatory as a number of candidates (100 hectares) of different parties (strata). Depending on the proportion of the strata, the ranking of each hectare has to be calculated. The basic principal of the d’Hondt divisor method is to divide the votes of a party (in our case number of hectare of the strata) by increasing even numbers 1 - 100. The resulting quotients of all strata are sorted descendingly. The allocation of the seats (in our case ranking number for the hectares) is carried out as follows: the highest quotient is related to the first seat (first ranking number), the second highest is related to ranking number two and so forth. With this method, the strata can be prioritised according to their real proportion. In the case that a quotient is occurring more often than the total number of hectares within the according stratum, this quotient is skipped. This procedure runs until 100 Ranking numbers are allotted to a certain stratum. The procedure can be explained by a simple example: In a given observatory only two strata occur, stratum A with 99 hectares and stratum B with only 1 hectare. Applying the divisor method and preference of the minority in case of equality the stratum B will be recognised at the 100th position, which is equivalent to the proportional coverage of the strata.

For the practical application of the ranking procedure, a computer programme was designed, which automatically determines a priority listing of all 100 sites of an observatory after the input of the habitat unit of each hectare. In the test phase of the program it became obvious that strata with a relatively lower rate of occurrence on the square kilometre occur with too high ranking numbers in the resulting list. This is correct according to the mathematical procedure but the intention of the frame conditions was to consider both, the coverage of the stratum and to ensure a relative high ranking number even for small strata. Therefore, the total areas of the small strata were up-rated by using the square root of the stratum size as basis for the determination of the ranking order. The changes in the results of this modified d'Hondt procedure are given in Tab. 2 (modified procedure). Besides the earlier occurrence of an item of smaller strata in the ranking list, the modification has the effect of clustering especially the small strata items in the higher ranked parts. This effect is desired because it ensures a minimum of replicates even for small strata in the case of a low sampling amount.

Tab. 2 Examples for the ranking position calculated after d'Hondt (original and modified) for different strata sizes

Stratum A	Stratum B	Position of B	Position of B (modified)
99	1	100	10
98	2	49; 99	7; 14
97	3	33; 66;100	6; 13; 20

The next step in the programme is the affiliation of the stratum-indicated ranking numbers to a certain hectare plot within the observatory. Therefore, the hectares of each stratum are set into a list by a random procedure. The first ranking number of a stratum is now affiliated to the first hectare plot in the randomized list and so forth. After application for each stratum, the ranking list with the location of the hectare plot is created and can be visualised in a grid structure of the observatory. The results of the ranking procedure are accessible and visualised under www.biota-africa.org (Southern Africa→ observatories).

As an example in Figure 4, the observatory #04 (Omatako / Toggekry) is shown with the randomly selected ranking order of the 100 ha sites. Five habitat units occurring with n = 4 to n = 53 hectare sites were differentiated on the observatory. This example shows that if a number of 25 sites (which is assumed as a reasonable n for soil analyses) is to be assessed on the observatory, all habitat types are represented with a frequency of 2-9. The rarest habitat type occurs for the first time in the ranking order with the number 7.

Coord.	0	1	2	3	4	5	6	7	8	9
0	44	90	83	89	72	**14**	**9**	79	35	74
1	97	81	88	47	67	**25**	95	**8**	**19**	41
2	64	**18**	40	36	62	42	43	60	30	46
3	**11**	**7**	29	57	52	31	78	87	**13**	70
4	59	**6**	39	99	**20**	**3**	58	55	**24**	50
5	38	69	85	66	93	82	94	51	**2**	65
6	54	75	77	91	86	37	84	71	73	45
7	80	**10**	61	**1**	56	100	26	96	**4**	28
8	48	63	**21**	92	53	34	76	**22**	33	**16**
9	**15**	32	98	**23**	68	**12**	**17**	27	**5**	49

Figure 4 Result of the ranking procedure at the observatory #04 Omatako (5 habitats indicated by different background colours; numbers: ranking priority, no. 1 –25 stressed)

3. Selection of biomes and land-use areas

Based on the experience of the dryland research group of the Biocentre Flottbek (University of Hamburg) and several counterparts in Namibia and South Africa, an area of one square kilometre in size was accepted as the basis for the investigations and monitoring within the different biomes and land-use systems. These areas are called in the following “biodiversity observatories” (obs.).

In a further step, the locations of the observatories in the study areas were fixed by use of expert knowledge, satellite data and field assessment of the suitability of the pre-selected area covering the major biomes. The final decision about selection was taken by all involved disciplines during a joint field trip. The transect with side branches and location of observatories is shown in Figure 2.

General remarks on the stratified, systematic random sampling with prioritisation:

Towards the end of this chapter, a general remark on the chosen strategy is necessary: The design is optimised to answer the questions in the project and to deliver required new solutions especially for the joint assessment of sites by different disciplines. The requirements can be summarised as follows:

- to capture the main and typical structure elements of the investigated region
- to create long-term monitoring sites
- to consolidate different disciplines in the best possible way
- to apply standardised methods along the transect

Each discipline has to deal with advantages and disadvantages in this procedure from both, the statistical point of view and the practical implementation. The procedure is therefore a compromise between the basic statistical requirements of sampling and the feasibility of the study and its scientific objectives. The applied techniques for selection and sampling can be summarised as follows:

- Selection of research area (observatory) – subjective
- Stratification – subjective
- Selection of sample sites (hectares) – random
- Selection of sample location – systematic
- Ranking of sampling sites – by adjusted proportion of strata

Inevitable potential problem areas in the procedure are given in the structure of the environment: i) linear landscape structures, ii) patchiness within the 1 hectare-sites, iii) temporal trends in the position of habitat units (shifts of vegetation units), and iv) the determination of borderlines in ecotones. Thus, the procedure has to be applied carefully and is strongly dependent on the quality of expertise and decisions regarding the selection of typical land-use units and characterisation of habitats. With consideration of these aspects, it provides a powerful tool for multidisciplinary field research.

2.2 Soil-related field work

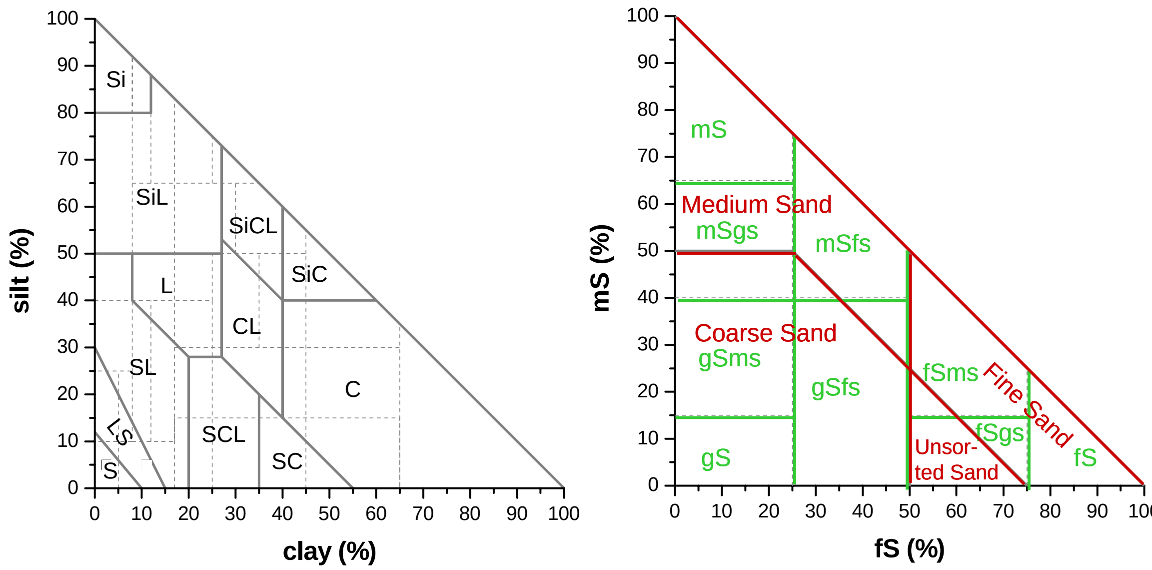
Soil data for this study comprises a total of > 600 soil profiles and additional 200 topsoil samples. Soil surveys took place in six campaigns from 2001 until 2005. The samples were subsequently analysed in the laboratory of the Soil Science institute in Hamburg.

The standardised documentation of soil inventory of the observatories follows the methodology of the above-introduced „ranking-procedure“. The standardised position of the soil profiles in a 1 hectare site was set 4 m south of the centre point. For the description and the sampling of the soils, a profile of 0.6-1.2 m depth is described with respect to the following parameters: stratification, texture, rock fragments, colour, humus content, lime content, soil and surface structure, crusting, bulk density, penetration resistance, distribution of roots. Each profile is documented with a photograph of the profile and the surrounding habitat.

Mixed samples for laboratory analyses were taken from all horizons of a soil profile. Additionally, defined sample volumes were taken using core samplers in order to determine the bulk density. While assessing the soil profile, the soil material was deposited on a large sheet. The profile was refilled after sampling to minimise any disturbance of the site and its vegetation.

The profiles are described according to the reference from AG Boden (KA4 1994, KA5 2005), FAO (guidelines for soil description 1990, 2006) and USDA (field book 2002). Information and best choice of description parameters is scattered in these references. Although in most cases comparable, in order to achieve a most detailed field description a mix of these references was applied.

The texture is analysed by use of the most detailed system of AG Boden and transferred into broader classes of the FAO system. Text information is given in the following structure: *loamy sand (Sl2)* with the FAO class in front and the AG Boden acronyms in brackets. Text information about pH-values (*slightly acid*) refers to the pH status in water by USDA (2002) as well as the degree of excavation difficulty.



S	LS	SL	SCL	SiL	SiCL	CL	L	Si	SC	SiC	C	HC
Sand	Loamy sand	Sandy loam	Sandy clay loam	Silt loam	Silty clay loam	Clay loam	Loam	Silt	Sandy clay	Silty clay	Clay	Heavy clay

Figure 5 Overview of texture classifications and abbreviations used in this study. Left) combination of German (KA4, dotted class borders, without abbreviations) and international texture classes (FAO, straight line, abbreviations explained in table below. Right) combination of German sand classification (KA4, green lines) and international classes (FAO, red lines)

2.3 Laboratory analyses

Sample preparation

Parameter	Description	Reference
Sample preparation in the field	samples with large amounts of stones are sieved to 2 mm in the field, the relation of stone to fine earth is determined by an electronic scale (0.1 g sensitivity) in the field. All other samples are transported to the lab without further preparation.	
Sample preparation in the lab	field samples are air dried, crushed and sieved to 2 mm (=fine earth fraction). A sub sample is ground to < 0.06 mm with a vibration disc mill (Conrad TS 100). If necessary, samples are dried with 105 °C in a drying oven.	
Bulk density	drying of 100 ml-samples with 105 °C, subsequent weighing of soil material by an electronic scale (0.1 g sensitivity)	Core method (BLAKE 1965)
Color	at the fine earth: with MUNSEL SOIL COLOR CHART, on wet and dry material	

Laboratory methods

Parameter	Description	Reference
pH-value	Preparation of two soil suspensions by addition of aquademin or 0.01 M $CaCl_2$ with a 1:2.5 relation (10 g dry weight + 25 ml solution). Measurement with a pH-electrode after 1 hour with repeatedly stirring of the suspension.	PSA, ISO 10390
Electrical conductivity EC	Measurement in the aquademin-solution (see pH-value) with a conductivity sensor. Additional preparation of a 1:5 solution.	
Total amount of nitrogen (TN)	A fine-ground sample (about 0.7 g) is combusted at high temperatures (900 °C) with oxygen, the released gases are separated and cleaned from water, and the NO_x is reduced to N_2. The N_2 is measured by thermal conductivity (vario MAX, Elementar Analysensysteme).	SSLMM-6B4a, ISO 13878

Parameter	Description	Reference
Total amount of carbon (TC)	A fine-ground sample (about 0.7 g) is combusted at high temperatures (900 °C) with oxygen, the released gases are separated and cleaned from water, and the CO is oxidized to CO_2. The CO_2 is measured by thermal conductivity (vario MAX, Elementar Analysensysteme).	SSLMM-6A2e
Amount of inorganic carbon (TIC)	A fine-ground sample (0.1 – 2.0 g) is heated and treated with 5 % HCl in a closed system. The released CO_2 is introduced in dilluted NaOH, where the amount of Carbon is measured by determining the change of electrical conductivity (Wösthoff-Apparatur).	
Amount of organic carbon (TOC)	The TOC is calculated by TC - TIC	
Particle-size distribution (PSD)	With a dried sample of fine earth a pre-test on the PSD is conducted: If the over standing water of a soil/water suspension is clear, the analysis is done only acc. to a). All other samples are analyses acc. to a) and b). Procedures of pre-treatment: • Addition of HCl to remove carbonates (in case of pH in H_2O > 7.4) • Addition of $Na_4P_2O_7$ to improve dispersion of particles • Ultrasonic treatment	PSA
	a) 300 g pre-treated fine earth is washed from fine-grained particles by repeated addition of $Na_4P_2O_7$ and ultrasonic treatment until the supernatant is clear. The dried sample is sieved through a set of sieves (2000, 630, 200, 125, 63 µm). The weight of each fraction is measured on an electronic scale (0.01 g sensitivity).	PSA
	b) 30 g of pre-treated fine earth is diluted in a 1 l sedimentation cylinder with $Na_4P_2O_7$ solution. The suspension is shaken overnight. After predetermined intervals, aliquots of 10 ml are removed with a pipette, with depth and time being based on Stokes' law. The aliquots (representing particle seizes < 63, < 20, < 6.3, < 2 µm) are dried (105 °C) and weighed on an electronic scale (1 mg sensitivity).	PSA
Elemental composition (XRFA)	A mixture of 8 g fine-ground sample and 1.6 g of HWC-wax is filled into a die of Ø 20 mm and pressed with 200 kN into a tablet. The tablet is converted in a X-Ray fluorescence spectrometer (Philipps PW-1404). The total concentration of the elements Al, Ba, Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Si, Ti and Zn is determined by X-Ray spectroscopy.	KIKKERT (1983)

Parameter	Description	Reference
Exchangeable cations and cation exchange capacity (CEC)	The exchangeable cations are removed with an excess of ammonium (5 g of air-dried soil, five extractions with 25 ml 1 M NH_4Cl each) and are quantified by atomic absorption and atomic emission spectroscopy (AAS). The ionic strength of ammonium is reduced to 0.01 M NH_4Cl and the adsorbed NH_4 extracted with 1 M KCl afterwards. The concentration of NH_4 is measured by photometry; the CEC is corrected for the soluted proportion of NH_4.	
AM-exchangeable cations	5 g of air-dried fine-earth are extracted with ammonium acetate two-fold (25 ml each, brought up to 50 ml as the final volume). For each step of extraction the sample is shaken (30 min) and centrifuged (2000 rpm for 10 min). The extracted cations are quantified by atomic absorption and atomic emission spectroscopy (AAS)	HELMKE & SPARKS (1996)
Water soluble anions and cations (1:1 extract)	30 g of air-dried fine earth are mixed with 30 ml water, shaken for 1 h and centrifuged. The supernatant is decanted and fine-filtrated (0,45 µm cellulose-acetate filter). The filtrate is divided in two bottles; to the one for the cation analyses conc. HNO_3 is added to prevent precipitation of salts. The cations are measured with AAS and AES, the anions by anion chromatography (IC). From the ion balance, the concentration of soluted carbonate/bicarbonate is calculated.	PSA (# 13)

HdB ALAILY, F. (2000): Carbonate und Salze. In: Handbuch der Bodenkunde. Ecomed Verlag, Chapter 2.1.5.5

ISO 10390 Deutsches Institut für Normung e.V. (DIN) (2005): DIN ISO 10390: Boden-pH Wert. In: Handbuch der Bodenuntersuchung, Abschnitt 3.5.1a. Wiley-VCH Weinheim, Beuth Verlag

ISO 13878 Deutsches Institut für Normung e.V. (DIN) (1998): DIN ISO 13878: Boden-Gesamtstickstoff, Verbrennung. In: Handbuch der Bodenuntersuchung, Abschnitt 3.4.1.58a. Wiley-VCH Weinheim, Beuth Verlag

PSA REEUWIJK, L. P. VAN (ED.) (2002): Procedures for Soil Analysis, 6th Edition. International Soil Reference and Information Centre, Wageningen: 101 pp.

SSLMM US DEPARTMENT OF AGRICULTURE, NATIONAL SOIL SURVEY CENTER (ED.) (1996): Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 3.0, Washington: 693 pp.

WRB FAO - ISRIC & ISSS (eds.) (1998): World reference base for soil resources. World Soil Resources Report 84, Rome. 88 pp.

BLAKE, G. R. 1965. In: C.A. Black (ed.) Methods of Soil Analysis, Part 1. Physical and Mineralogical Properties, Including statistics of Measurement and Sampling. ASA-SSSA, Agronomy Monograph 9: 374-390.

HELMKE, P. A. & SPARKS, D. L. (1996): Alkali Metal Properties. In: Bartels, J. M.(Eds): Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, Inc., Madison, Wisconsin. pp. 551

KIKKERT, J. (1982): Practical geochemical analysis of variable composition using X-ray fluorescence spectrometer. Spectrochimica Acta.Vol 38b, No 5/6, pp. 809-820, 1983.

2.4 Data processing

2.4.1 Laboratory

Electric conductivity in saturated paste EC_e:

EC_e is a frequently used parameter to characterise the degree of salinity in the soil under water-saturated conditions, which should reflect the best possible estimation of field conditions when not using techniques to extract water out of the bulk soil (RHOADES et al. 1999). In this study, the EC_e is important for two purposes: i) to identify the degree of salinity in order to classify the soils, and ii) to identify the degree of salinity and the potential salt stress for organisms under field conditions.

In comparison to the $EC_{2.5}$ and EC_5, the EC_e includes the influence of the soil texture with its different pore space distribution and abilities to store water. Comparing two samples with different textures (e.g. pure sand and pure clay) may illustrate this process. Pure clay may provide a total pore volume of 58 %, whereas the pure sand with 36 % is already saturated with less water than the clay. Therefore, the maximum possible dilution of the salts in the bulk soil is restricted by the maximum of the added water. When assuming the same amount of salt in the soils, this results in a higher EC_e in the sand as it is already saturated with less water than the clay. The $EC_{2.5}$ would give the same electric conductivity for both texture classes.

Despite the considerations regarding the ability of the ECe to reflect natural conditions, it is used for classifying salinity of soils and often required as a parameter in soil classification systems. Thus it is necessary to produce EC_e values for all soil samples in this study. As the production of saturated paste is very time-consuming and the point of saturation is not exactly detectable, a calculation procedure that includes the water retention capacity of the soil texture is used (after ALAILY 2000). The advantage of this calculation is that it is referring to the water storage capacity and excludes the air capacity. In the preparation of a saturation extract, the latter is also included. Therefore, the calculated EC_e should be a better estimate of the field condition with the maxima of water storage in the soil. The calculation after ALAILY (2000) is used here as the best available measure for the electrical conductivity in saturation paste (EC_e). It is calculated by

$$EC_e = \frac{250 * EC_{2.5}}{Wc}$$

With EC_e = electric conductivity in saturation extract [mS cm^{-1}], $EC_{2.5}$ = electric conductivity of the 1:2.5 dilution [mS cm^{-1}], and Wc = water capacity, which can be used equivalent to field capacity (ALAILY 2000). Field capacity is derived from the estimates by means of soil texture classes and medium bulk density after KA4 (AG BODEN 1994).

In many arid regions, the highly soluble salts are dominating the total amount of salts in the soil. Highly soluble is defined by a higher solubility than gypsum. However, in the interpretation of the calculated EC_e one has to consider possible precipitations of the salts under higher concentrated conditions present in the saturation extract. This is especially important for the lower soluble salts like gypsum that would not solute in a concentration resulting in an EC of 2.13 mS cm^{-1} (ALAILY 2000). In such cases an overestimation of the EC_e due to the calculation would occur. ALAILY (2000) provides an equation for the EC_e in the case of gypsum rich soils:

$$EC_e = \left(\frac{250 * (EC_{2.5} - 2{,}13)}{Wc} \right) + 2{,}13$$

However, this is only applicable when the $EC_{2.5}$ exceeds 2,13 $mScm^{-1}$ and one has to be sure that the gypsum is dominating the EC. ALAILY (2000) defined gypsum rich soils by material containing more than 0.93g kg^{-1} S or 0.51 % gypsum. This is problematic in cases where higher sulphur contents are caused by crystallised gypsum that has a lower solubility than gypsum in a powdery aggregation.

In this study, the part of the EC caused by highly soluble salts is calculated by subtracting the EC_5 from the $EC_{2.5}$. The result gives the EC of highly soluble salts in the EC_5. The doubled result stands for the EC of high soluble salts in the $EC_{2.5}$. To segregate samples with considerable amounts of low soluble salts and an $EC_{2.5}$ that could result in saline conditions when calculating the EC_e, the following procedure is used:

The EC_e in samples with an $EC_{2.5}$ > 400µS cm^{-1} showing less than 75 % of high soluble salts are calculated by an equation based on the gypsum example above.

$$EC_e = \left(\frac{250 * (EC_{2.5} - EC_{LSS})}{Wc} \right) + EC_{LSS}$$

With EC_e = electric conductivity in saturation extract [mS cm^{-1}], $EC_{2.5}$ = electric conductivity of the 1:2.5 dilution [mS cm^{-1}], Wc = water capacity and EC_{LSS} = electric conductivity of low soluble salts in the $EC_{2.5}$.

Osmotic potential:

The ecological importance of salt influence can be illustrated by the osmotic potential, which could reach considerable values in salt affected soils and therefore restrict the water availability. Therefore, the osmotic potential is used as an estimate for the soil quality in terms of water availability. In the natural, mostly undisturbed and non-irrigated ecosystems researched in this study, the osmotic effect is assumed to dominate the site characteristics when salinity is high.

Besides the requirements for classification purposes mentioned above, the EC_e can be used to estimate the osmotic potential under saturated (here field capacity) conditions by the equation

$$OP_e = 0.36 * EC_e$$

with EC_e [mS cm^{-1}] and OP_e =osmotic potential under field capacity [bar] (after ALAILY 2000, MACBRIDE 1994). SPARKS (2003) states a rather similar multiplication factor of 0.4.

When interpreting the results of this calculation, it has to be considered that the values represent conditions under field capacity with the maximum amount of water in the soil. When the water content decreases, the osmotic potential will increase until the first salts precipitate. As highly soluble salts are dominating in most of the soils in this study, the point of precipitation will only be reached with relatively low water contents. This will result in to some extent very high osmotic potentials during the drying period of the soil. As a rule of thumb, the osmotic potential is doubled when the water content is halved.

Total reserve of bases (TRB)

The total reserve of bases (TRB) is a parameter used in the WRB (FAO 1998, 2006) for the characterisation of the weathering status of the substrate. It can be used as an alternative estimate for the amount of weatherable minerals in the characterisation of the ferralic horizon. In this study, the TRB is used as an integrative parameter for the characterisation of the base reserves in the substrates. The TRB is calculated as the sum of the bases Ca, Mg, K and Na [$cmol_c$ kg^{-1}] using the analyses of total element contents according to XRFA.

Gypsum content

The classification according to WRB (FAO 1998, 2006) requires the content of gypsum for the selection of the diagnostic gypsic horizon as well as for gypsiric material requirements. According to ALAILY (2000), the relationship between the total content of suphur and the amount of gypsum is approximately 5.4 (S [%] * 5.4 = gypsum [%]). Sulphur contents are derived from XRFA analyses.

2.4.2 Satellite data, aerial photographs and digital elevation models (DEM)

Satellite data and aerial photographs for maps are provided by the subproject ‚Remote sensing' (DLR, German Aerospace Agency). Additional aerial photographs were purchased in order to analyse time series with respect to erosion features in the Koeroegabvlakte. The pre-rectified and geo-referenced data was enhanced in accuracy by the use of field-derived reference points and tracks from GPS readings (Garmin 12, III+, 60) in several field campaigns. A correction of the image coordinates was carried out with ERDAS Imagine ©

software. In case of non-availability or quality problems, the observatory picture data was derived from Google Earth © screenshots, i.e. Digital Globe images.

Basic data for the digital elevation models (DEM) in a 100 m grid was derived from initial DGPS surveys of all observatories by a private company. The data has a mean height accuracy of 0.5 m. DEMs were created through own work with kriging height data with Surfer 6.0 © (Golden Software) or ArcView 3.2 © (ESRI) software. Regional DEMs were created by use of the Shuttle Radar Topography Mission data set (SRTM) in a spatial 90 m resolution.

2.5 Soil classification

The documented soils were classified according to the World Reference Base for Soils Resources (FAO 1998). The WRB was originally developed as a reference base for improved communication. However, it increasingly becomes a classification tool in national contexts and the revised version of the WRB (FAO 2006) constitutes further development in this direction.

An alternative with a finer hierarchical framework and therefore probably a better system for the detailed description of soil parameters is the USDA Soil Taxonomy (2003). A major difference of WRB and Soil Taxonomy is that soil climate is not part of the system, except in so far as the effects of climate affect soil properties. The decision to use the WRB was based on some considerations at the beginning of the field work, i) soil data should fit into the framework of the national soil database in Namibia which already uses WRB; ii) information about (regional) temperature and moisture regime are not necessary in the context of this study’s scientific objectives. Moreover, validation with test sites revealed no advantage in the precision of soil description for this study. The description of the soils on the family and series level of the USDA system provides a detailed system to express soil properties by possibilities of adding parametric attributes. However, a proper application of the WRB enables the same degree of details in description, particularly the revised version with the possibility to qualify the texture characteristics.

The publication of the revised version of the WRB (FAO 2006) came too late to incorporate all aspects in this study. Therefore, the pedodiversity analyses as well as the soil maps still use the original WRB system (FAO 1998). However, each profile of the database is classified by WRB 2006 and the presented reference profiles provide both classification systems. Moreover, each regional soil inventory is discussed briefly with respect to changes by applying the WRB 2006. A complete list of all soil profiles used in the study including both WRB classifications (FAO 1998 & 2006) is provided in appendix I.

The degree of description details (number of qualifiers and pre- and suffixes) in the WRB is provided on different levels. For the reference profiles, all possible qualifiers are included in the description. For soil maps and frequency graphs, different numbers of additional qualifiers are used in order to achieve a compromise between degree of detail and a clear overview. Although the WRB has no further differentiation levels in the use of the qualifier, the terms 1^{st} and 2^{nd} qualifier level are used to identify how many qualifiers are in use.

With respect to the pedodiversity analyses, additional classifications were applied in this study. These are i) a strictly parameter based classification by use of the parameters pH-value, EC, texture, organic carbon and the available rooting space and ii) a parametric based overall integrative estimation of the pedodiversity per observatory by use of convex hull algorithms. Both approaches are explained in detail in chapter 6.

3 Soil inventory and soil variability on studied areas

The BIOTA Southern Africa Transect and corresponding observatories provide the research infrastructure for this study. The transect of 2,000 km length stretches from northern Namibia to Cape Town in South Africa with different sidelines and additional study sites. Thus different climatic conditions typical for this part of the subcontinent are reflected. These are namely the tropical summer rainfall regime in the northern half of the transect and the winter rainfall regime in the southern part, both decreasing and overlapping in the central region along the Orange River and the southern Namib desert. Mean annual precipitation is between 10 mm in the costal plains of the Namib Desert up to 500 mm in northern Namibia and the Cape region where even rainfall amounts of 2000 mm are noted in exceptional topographic locations such as the Table Mountain. Except for such azonal sites, mean potential annual evaporation in all regions exceeds the amount of rainfall resulting in climatic regimes from hyper-arid to semi-arid. Summer rainfall is characterised by a precipitation season with erratic thunderstorms from October to April while the winter rainfall occurs from June to September with Atlantic cyclone fronts with less intensive precipitation events.

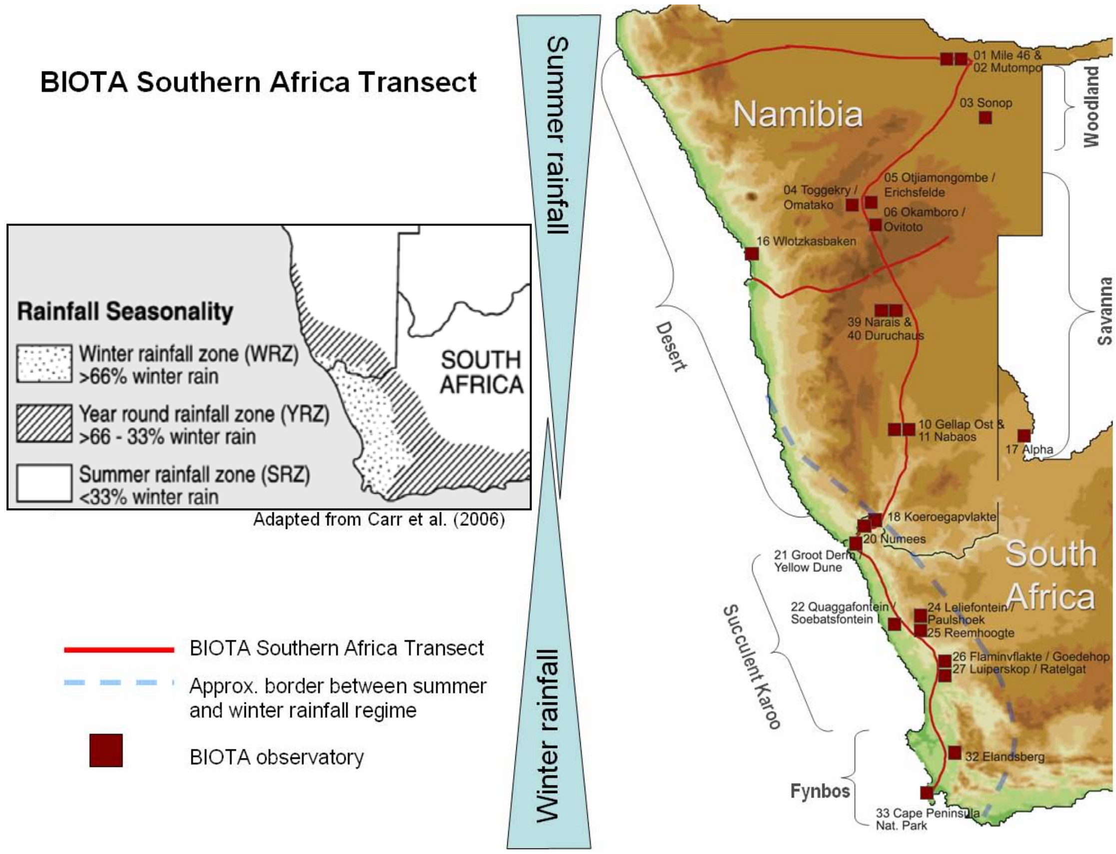


Figure 6 Overview of the BIOTA Southern Africa transect incl. the location of the observatories relevant for this study

The observatories are situated in five main biomes (see Figure 6). The Woodland biome is situated in the north-east of Namibia. Compared to the Savanna biome further south on the transect, the higher rainfall allows a transition from the Thornbush Savanna into a Tree Savanna and dry Woodlands on the sandy substrates of the Kalahari sediments. Striking features of the landscape are east/west stretching linear dune systems. Compared to other Namibian regions mean annual rainfall is relatively high with 475 - 550 mm and enables a low intensity rain-fed subsidence crop production with Mahangu and Maize in addition to the livestock grazing. Three observatories (#01, #02, and #03) are located in this biome.

The Savanna biomes cover the largest part of the transect and incorporate Thornbush Savanna and the Nama Karoo Savanna, a drier, dwarf-shrub characterised vegetation in southern Namibia. Mean annual rainfall ranges from 450 to 150 mm and substrates and habitats range from shallow rocky mountainous areas over loamy plains to sandy dune systems in the east neighbouring Kalahari sediments. Land-use is dominated by livestock grazing with cattle and further to the south with small-stock such as sheep and goats. The observatories #04, #05 and #06 are located in the moister Thornbush Savanna while the numbers #39/#40 are situated in a transition zone to the Nama Karoo. Here the sites #10 and #11 represent the driest savanna elements with 150 mm annual rainfall. The observatory #17 is situated in the Kalahari sediments and characterised by grass dominated vegetation.

The Desert biome, namely the Namib Desert, covers a large area in the west of Namibia and stretches into the north-western part of South Africa with a transition zone to the Succulent Karoo biome. The Namib receives a mean annual rainfall of 10 mm near the coast up to > 100 mm on the eastern border, the escarpment. Rainfall is highly variable with long periods of no rainfall along the coast. Here, additional moisture is provided by the characteristic fog. Analogue to the increasing rainfall inland, a high turnover in vegetation type occurs in west/east direction from microbiotic crusts and lichens to savanna elements. Land-use in this biome is characterised by contrasting elements such as nature conservation of the unique landscapes, tourism and mining activities of minerals, diamonds and uranium. Besides mining also rapid development of settlements increase the pressure on water resources. The observatory #16 is situated on the coastal plain of the central Namib Desert while the observatories #18, #20 and #21 are located in the southern Namib already part of the Succulent Karoo.

The Succulent Karoo biome of southern Africa is prominent as one of the centres of endemism and biodiversity and cover the largest part of the transect in South Africa. It is characterised by a winter rainfall regime with 50 – 250 mm mean annual rainfall and bordered by the desert in the northwest, the Nama Karoo Savanna biome in the north and east and by the Fynbos biome in the south. Analogue to the exceptional species rich flora with mainly leaf succulent species, the landscape is characterised by small scale changes of habitats by morphology and substrate changes. Land-use is characterised by small stock farming and mining activities. The observatories #22, #24 and #25 are situated in the central Succulent

Karoo while the numbers #26 and #27 are situated in the southern part with the exceptional features of large quartz fields in the Knersvlakte.

The two southern-most observatories of this study are located in the Fynbos biome. The Fynbos biome is part of the Cape Floristic Region, a global biodiversity hotspot located in the southern and western part of South Africa. With increasing rainfall the climate can be described as Mediterranean, with the majority of rainfall in the winter months. Spatial variation in mean annual rainfall ranges from 250 mm in coastal lowlands up to 2000 mm on exceptional positions such as the Table Mountain. The two observatories of this study (#32 and #33) are characterised by approx. 500 mm rainfall and comprise different kind of Fynbos and land-use. The Lowland Fynbos of #32 in the Swartland area with nutrient rich substrates is a remaining fragment due to agricultural activities (crop production). The Fynbos of the Cape Peninsula is characterised by nutrient-poor bedrock and is situated in a large conservation are, the Table Mountain National Park.

Tab. 3 Overview of the observatories and number of profiles and additional topsoils selected in this study by ranking procedure

Nr.	Name		Profiles	Topsoil (add.)	Additional
01	Mile 46 Research St.	NAMIBIA	1	14	5 profile transect
02	Mutompo		15	-	9 profile transect
03	Sonop Res. Station		-	-	12 profile transect
04	Toggekry (Omatako)		40		100 topsoil samples on ha 39, termite mounds
05	Otjiamongombe		26	-	
16	Wlotzkasbaken		15	5	
39	Nareis		25		
40	Duruchaus		25		
10	Gellap Ost		17	5	
11	Nabaos		17	5	
17	Alpha	SOUTH AFRICA	25		15 profile transect
18	Koeroegapvlakte		20	5	5 profile heuweltjietransect
20	Numees		25		15 profile geodiversity survey, small scale changes
21	Groot Derm (Y. D.)		6	9	
22	Soebatsfontein (Quaggasfontein)		25		10 profile transect, 4 profile transect heuweltjie
26	Flaminkvlakte		16	10	
27	Luiperskop		17	10	
32	Elandsberg		15	10	
33	Cape Pensinsula NP		25		

This study was restricted to the 22 observatories of the BIOTA Southern Africa transect introduced above. For these areas of similar size (100 ha each) the soil scientific data base to describe soil inventory and to derive indices of pedodiversity is nearly constant, as given by the number of profiles and of topsoil samples in Tab. 3. Some additional investigations on the observatories are used to improve the description of the soil inventory.

In dryland areas agriculture is marginal and current soil classification and soil maps typically describe the pedosphere to be less diverse compared to more intensely utilised areas in temperate zones. This underestimation of arid soil diversity is either due to the low number of studies existing in these climatic zones and / or is due to the shortcomings of the current international classification systems which are mainly designed for agricultural purposes and often fail to describe the actual existing variation in arid soils (HARTEMINK 2002). For the broader investigation area the existing soil maps (FAO (1995), SOTER Namibia, COETZEE (2001), „Land Type Series" DU PLESSIS (1987)) provide information on the range of soil types. Recent regional studies about the genesis and properties of soils are described in a number of publications (e.g. BEUGLER-BELL 1996, ABRAMS et al. 1997, BRUNOTTE & SANDER 2000, KEMPF 2003, EITEL & EBERLE 200l, 2002, WATKEYS 1999, DAHLBERG 1999, BURKE 2002, MILLS & FEY 2003, MILLS et al. 2006, FRANCIS et al. 2007, amongst others). Intensive research on ecological processes along climatic gradients on the southern African subcontinent has been done by the IGBP[1] Kalahari Transect Project (e.g. SCHOLES & PARSONS 1997, WANG et al. 2007). However, that study aimed to minimize the influence of the soil parent material (by the restriction of the transect to sandy Kalahari substrates) in order to analyse the effects of climate (RINGROSE et al. 1998). In contrast to the Kalahari transect, along the BIOTA-Southern Africa transect the impact of the climatic gradient on soil properties is strongly overlain by the influence of variations in the soil parent material. This leads to a strong influence of the regional geodiversity which has to be considered for the interpretation of the climatic gradient, but furthermore provides insight into the role of local abiotic heterogeneity.

The following chapters focus on the inventory of soil taxa and on the variability of selected soil parameters on the investigated sites. Each site is introduced by a regional overview and a description of the observatory with regard to topography and vegetation patterns. The description of the soils starts with an inventory based on WRB classification units (FAO 1998, FAO 2006), gives special remarks to problems of classification, introduces the features and properties of reference profiles and a brief presentation of the variability of selected soil properties on the 1 km^2 area of the observatories. The latter is combined with a discussion and concluding remarks regarding the ecological important soil features and the role of soils in the landscape evolution of the certain area. A complete list of soil classification and laboratory analyses for all profiles can be found in the appendix I.

[1] International Geosphere–Biosphere Programme

3.1 Observatory 01 (Mile 46) & 02 (Mutompo)

3.1.1 Regional overview

The pair of observatories #01 (Mile 46) and #02 (Mutompo) are situated approx. 70 km south west of Rundu in the Kavango Region. Both observatories are separated by a fence; the western area is used as a governmental research farm since 1985; the eastern area is subject to communal land-use.

Compared to other Namibian regions mean annual rainfall is relatively high with 550 mm. Rainfall is highly seasonal with a maximum in January and no significant rain events between May and September.

The region belongs to the north eastern Kalahari Woodlands (MENDELSOHN & OBEID 2003) which are characterised by a mosaic of dry forests or open woodlands with numerous hardwood species, including *Baikiaea plurijuga*, *Pterocarpus angolensis* and *Guibourtea coleosperma* and more open savanna vegetation (for a detailed overview see STROHBACH & PETERSEN 2007 and GRAZ 2006). On the research station there is cattle farming in a fenced camp system, while the communal area is organised as an open access system with cattle grazing and small units of crop production near the settlements (PRÖPPER 2005). The majority of crops are grown on rainfed dryland fields. Mahangu (Pearl millet, *Pennisetum glaucum*) is the dominant crop in the region, and about 75 % of the cultivated area is used for its production while the rest is used to grow maize and sorghum. The most important pressures on the environment are the clearing of natural vegetation for crop cultivation and the widespread bush fires, which are in many cases of anthropogenic nature. Additionally, the logging and collection of wood for energy and carving purposes reduces the natural resources.

The topography of the area is flat. Slight differences in height (few meters) are evident in east/west leading linear structures which show striking similarities to the longitudinal dunes evident in large parts of the Kavango region. However, a clear distinction of dunes and interdunal streets is not detectable by topography but often by vegetation structure which reflects the dune remnants with their typical soil inventory. Remains of interdunal streets or "dune valleys" are in general rather open bush- or grasslands whereas the dunes are dominated by woodland vegetation. In general a relatively dense vegetation cover is found in the area, indicating that environmental conditions today are not conducive to linear dune construction in this region. THOMAS et al. (2000) assume a dune construction phase between 43 and 21 ka based on optical age data of samples in the region further south. Interestingly the samples originate from a maximum of only 1.9 m depth leading to the assumptions of much older material below.

Geologically, the region belongs to the Kalahari group characterised by quaternary sediments, i.e. undifferentiated, unconsolidated sands and firm to massive calcretes. The drainage system of the entire area is heading north towards the Okavango River that is draining into the Kalahari Basin (Okavango delta). Aquifers in the Kalahari sediments provide a relatively high groundwater table of 40-80 m below the ground in the investigation area (OBEID & MENDELSOHN 2001).

Soil information on the broader study area is provided by the FAO soil map (1997) and the AEZ (COETZEE 2001). The area is dominated by cambic Arenosols, albic Arenosols, calcic Xerosols (FAO 1997, revised Legend). The database of COETZEE (2001), following the World Reference Base for Soil resources (FAO 1998), indicates Ferralic Arenosols as dominant soil units and associated Petric Calcisols. Both sources provide a rough inventory of the soil units without a regionalisation and without data on soil properties.

3.1.2 Observatory description

The two observatories are situated close to each other along the fence of the eastern border of the research farm Mile 46. Both sites display similar landscape structures allowing comparisons of the different land-use practises. Due to only marginal differences in the topography, the habitat types for the ranking procedure were based on the structural vegetation units: closed woodland, open woodland, mixed savanna, acacia woodland and thicket. The vegetation structure shows an east/west linear orientation best described as “banded vegetation”.

Due to the great abiotic similarity of both observatories, only the observatory #02 (Mutompo, communal area) is presented in detail (aerial photography in Figure 8). The habitat type ‘closed woodland’ represents the dry forest which forms the dominant habitat and builds the matrix vegetation in the northern and southern part of the observatory. The open woodland marks the transition zone to the central part with more open, bush dominated habitat types. The densest thicket is situated in the transition zone to the woodlands in the southern part of the observatory.

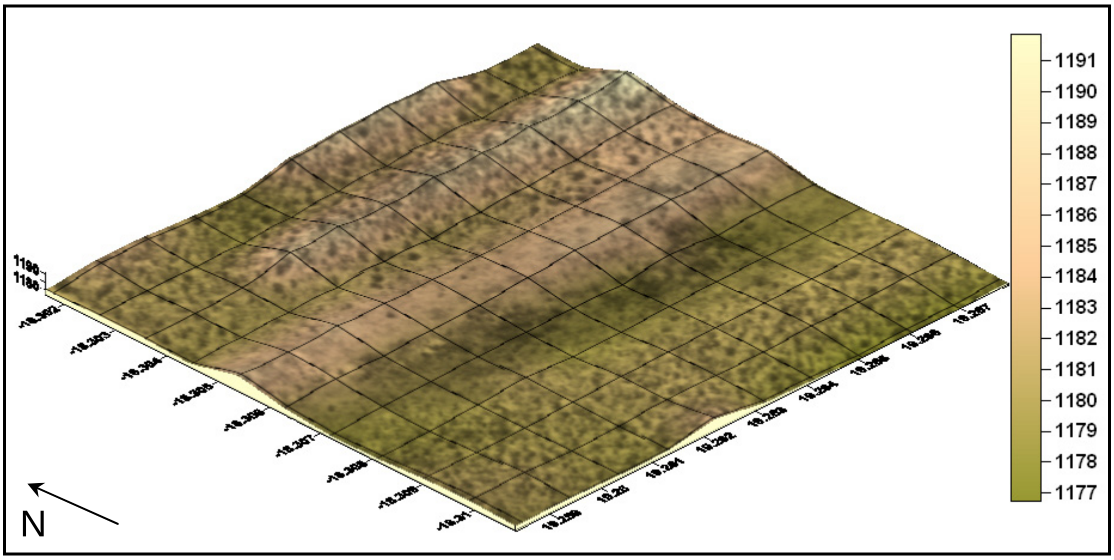


Figure 7 Topography of observatory #02 Mutompo (height in m asl)

The topography of the observatory is flat to slightly undulated with heights from 1177 to 1192 m. The central part of the observatory is slightly higher than the closed woodland in the surrounding. As this part is interpreted as the interdune remnant, this is in contrast to other areas with more distinct longitudinal dunes and interdunal corridors which are always situated in the deeper location. Strong erosion events which affected the dunes stronger than the interdunes might be the reason for this “inverse topography”. The deepest areas of the observatory are situated in the southern central part and show the densest bush cover. Such dense bush patches are common along the dune streets in the region. Often these linear structures bordering the dunes have the deepest topographic positions and are the origin for natural drainage systems parallel to the dune system. In their simplest forms the drainage systems occur as small pans that are waterlogged for a short period of the year. In areas with higher rainfall or lower infiltration these chains of pans can build small *omurimbi* (shallow ephemeral drainage systems; singular – *omuramba* – a wide, flat watercourse with no visible gradient). In the observatory a few small pans are situated in the thicket habitats at the deepest locations. Probably these locations already belong to the margin “catchment” of the *Mpuku omuramba* which has its origin in the western and south western surrounding of the investigated observatories.

3.1.3 Soils

3.1.3.1 Main soil units

A total of 24 soil profiles of 2 m depths and 19 additional topsoils were documented and sampled at the two observatories. The different soils units of the observatory #02 Mutompo and their distribution are shown in Figure 8. Almost all profiles are classified as Ferralic Arenosols (Figure 9), which are subdivided by a second qualifier to eutric and dystric. One single profile situated close to a small pan is classified as Stagnic Regosol. Prominent mottles of iron oxides indicate seasonal water logging for this profile. The stratification of the substrates with sharp borderlines in the profile is most likely created by fluvial influence.

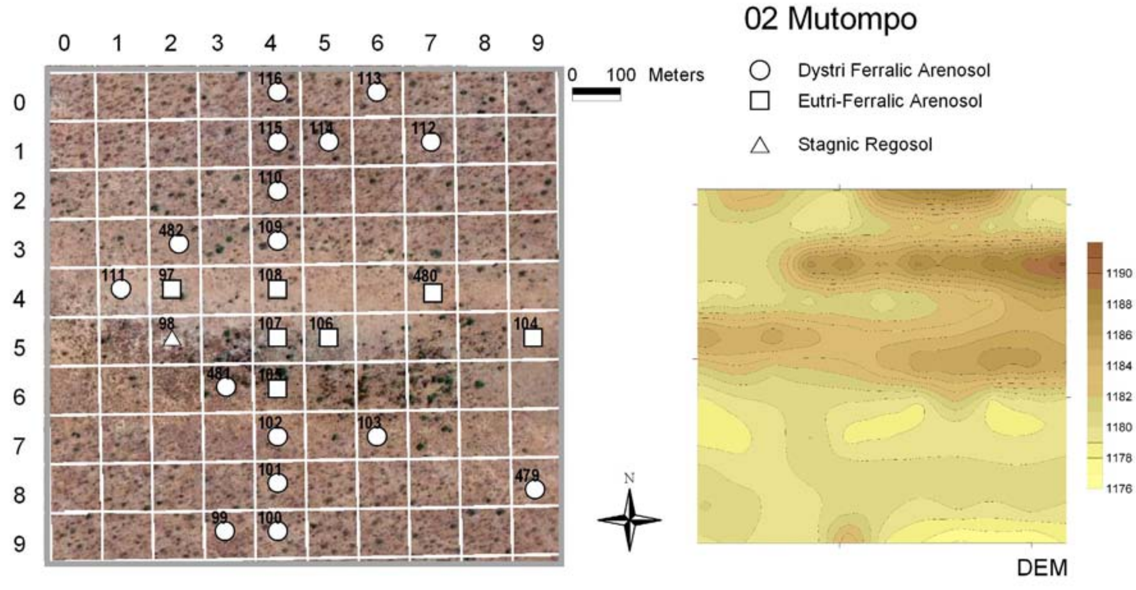


Figure 8 Distribution of soil units (WRB 1998, 2nd qualifier level) on obs. #02 Mutompo with ha-grid, position and number of soil profiles and elevation model

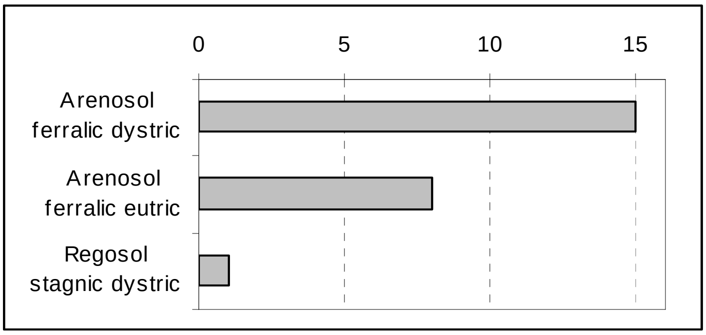


Figure 9 Frequency distribution of WRB (1998) soil units in observatory #02 (Mutompo)

The Dystric Arenosols are the dominant soil types of the dry forest habitat. They consist of deep (> 2 m) greyish to pale brown medium sand (mS). The topsoil shows a weak accumulation of humus and is covered with a thin layer of bleached sand. A sparsely found organic layer consists of windblown leafs of dry forest trees. Strongly developed, black microbiotic crusts of a few mm thickness are evident in few patches. The pH-values are strongly acid to very strongly acid, the nutrient status and CEC of these soils are very low. Many profiles show fragments of charcoal which are commonly accumulated in the upper part of the profile, but they can also be found scattered across the deeper parts of the profile.

Vertical chains of charcoal which originally belong to one single root were found in some profiles. This indicates the evidence of deep in situ burning or carbonisation of organic components from the surface downwards into the profile during common fire events in this ecosystem. The high porosity of the sandy substrate and the dryness of the soil obviously enable this process.

The Eutric Arenosols concentrate on the more open savanna habitats and the thicket sites in the central part of the observatory. Prominent features of these soils are the darker colours across the entire profile and slightly higher clay contents. The pH-values are slightly acid to neutral and the nutrient status and CEC are slightly higher than in the Dystric Arenosols. The depth of the profiles is in most cases up to 2 m, only in one profile a calcrete occurs in 1.75 m.

3.1.3.2 Remarks on classification

Classification was carried out with the WRB (FAO 1998). Although only a maximum of two qualifiers per soil unit could be assigned these were sufficient to delineate the most important soil features (texture, low CEC, base saturation and pH-value) and differentiate various soil units. However, one shortcoming of the FAO soil description is that soil texture classes do not distinguish between pure sand and slightly loamier textures in interdune habitats as probably the main driving property for the differences of the soils in this observatory. The differentiation between eutric and Dystric Arenosols was only possible by lab analyses (pH, CEC), though the texture differences were already detectable in the field.

The light colour of the substrate, the bleached sand layer and the low pH-values indicate an acid bleaching (podsolisation). Although the requirements for the diagnostic albic horizon were fulfilled for most of the Dystric Arenosols, I decided to ignore this feature as field observations showed that the light colour is due to the soil parent material. Additionally, no accumulation horizons were found up to a depth of 2 m.

Based on the very low CEC (< 4 $cmol_c$/kg) resulting from the low clay content (< 8 %) and organic matter (< 1 %) the qualifier ferralic is used.

The application of the new edition of the WRB (2006) reveals only minor changes. The new introduced qualifier “greyic” now allows expressing the signs of podsolisation in the topsoils. All profiles fulfil the “greyic” requirements but the signs of podsolisation, especially the uncoated sand grains, are more dominant in the Dystri-Ferralic Arenosols.

3.1.3.3 Description of reference profiles

Reference profile # 1

Profile: **113**	Ha: **06**	Classification (WRB 1998)	**Dystri-Ferralic Arenosol**
		(WRB 2006)	**Ferralic Arenosol (Dystric, Greyic)**

cm	Horizon	Description
		Thin organic layer of leafs, accumulation of 2mm bleached medium sand, very low penetration resistance (dry)
10	Ah	Medium sand (mS), single grain structure, brownish dark grey, Munsell 2,5Y5/2 dry and 2,5Y3/2 moist, 20-50 roots/dm^2, dry, low excavation difficulty
30	AC	Medium sand (mS), single grain structure, brownish-grey, Munsell 10YR6/2 dry and 10YR4/1 moist, 11-20 roots/dm^2, dry, low excavation difficulty
50	C1	Medium sand (mS), single grain structure, greyish pale brown, Munsell 10YR6/3 dry and 10YR5/3 moist, 11-20 roots/dm^2, dry, low excavation difficulty, few charcoal fragments
80	C2	Medium sand (mS), single grain structure, pale brown, Munsell 10YR7/3 dry and 10YR5/3 moist, 5-10 roots/dm^2, dry, low excavation difficulty Many charcoal fragments at 80 cm
210	C3	Medium sand (mS), single grain structure, pale brown, Munsell 10YR7/3 dry and 10YR6/4 moist, dry, very few Fe-mottles

Figure 10 Description of profile 113

The reference profile 1, a Dystri-Ferralic Arenosol (Figure 10) is a typical example for the soils developed in the pure sands. The texture is dominated by medium sand (64 – 79 %) and shows no significant changes over the entire profile or signs of layering. The very strongly acid pH-values are nearly constant with depth (Figure 11). The organic carbon reaches ~ 0.4 % in the topsoil and shows a slight decrease with depth. The electrical conductivity (EC) is very low with 18 µS cm^{-1} in the topsoil and values < 5 µS cm^{-1} in the lower horizons. These values indicate both, an input of rainwater with low ionisation and a deep drainage of the soil. The quartz rich dune sands are characterised by very low total content of elements (Mg and K < 0.1 g kg^{-1}) and no significant changes across the entire profile. This results in a very low base reserve (TRB) of the substrate. With values of 10 mmol$_c$ kg^{-1} in the topsoil and around

5 $mmol_c\ kg^{-1}$ in the deeper horizons the CEC is very small (not shown in graph). The same is true for the water soluble ions (2.7 $mmol_c\ kg^{-1}$). To summarise, these profiles describe extremely nutrient poor soils with a deep drainage and distinct signs of acidification.

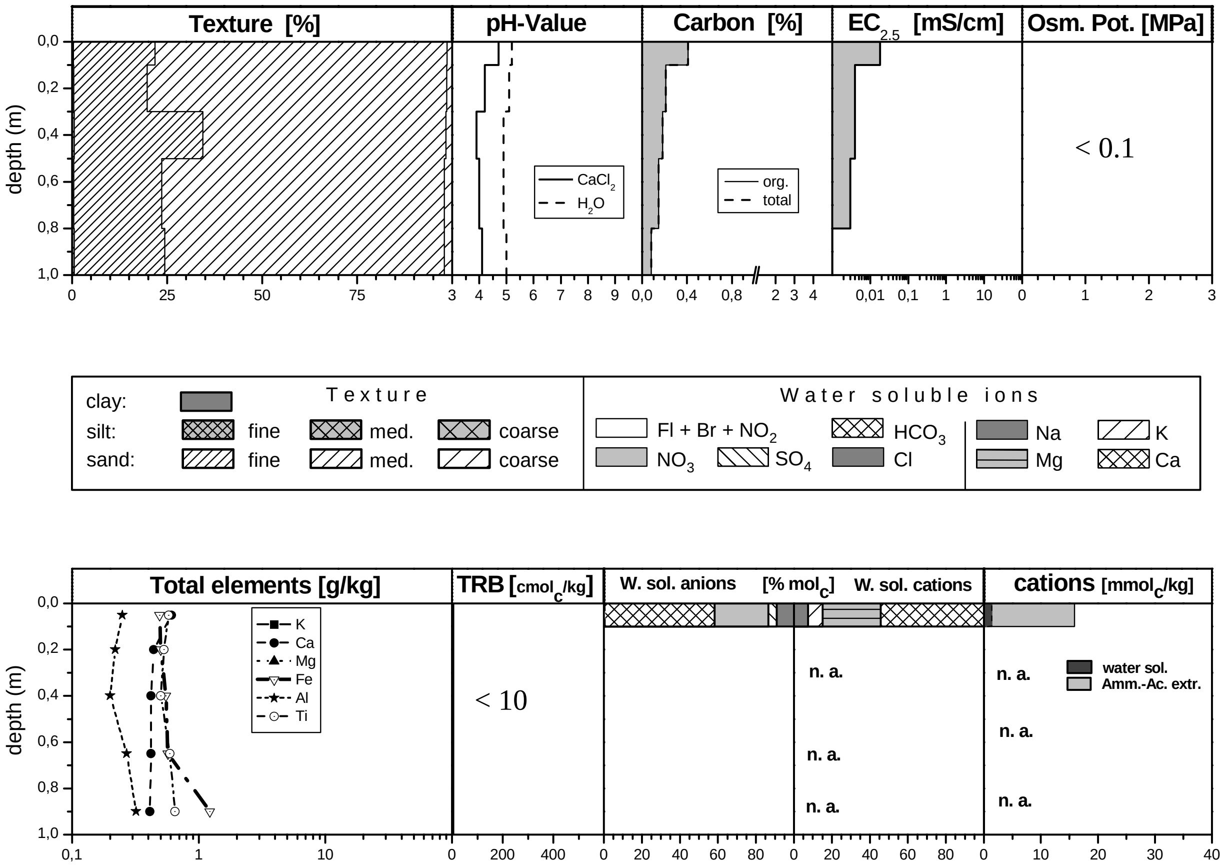


Figure 11 Properties of profile 113

Reference profile # 2

Profile: **105**	Ha: **64**	Classification (WRB 1998) (WRB 2006)	**Eutri-Ferralic Arenosol** **Ferralic Arenosol (Dystric, Greyic)**

Horizon	Depth (cm)	Description
		Thin organic layer of leafs, accumulation of single bleached sand particles, very low penetration resistance (dry)
Ah	10	Medium sand (St2), subangular blocky structure, grey brown, Munsell 10YR5/3 dry and 10YR3/2 moist, 10-20 roots/dm^2, slightly moist, low to medium excavation difficulty
Ah2	40	Medium sand (St2), subangular blocky structure, greyish brown, Munsell 10YR4/3 dry and 10YR3/3 moist, 10-20 roots/dm^2, slightly moist, low to medium excavation difficulty
B1	70	Medium sand (St2), subangular blocky structure, greyish brown, Munsell 10YR5/3 dry and 10YR4/2 moist, 10-20 roots/dm^2, slightly moist, low to medium excavation difficulty
B2	145	Medium sand (St2), brown, Munsell 10YR5/8 dry and 10YR4/4 moist, slightly moist
B3	200	

Figure 12 Description of profile 105

This Eutri-Ferralic Arenosol (Figure 12) is an example for soils developed in the loamier central part of the observatory. The group of these soils is not as homogenous as the Dystri-Ferralic Arenosols but can be described sufficiently by this reference profile. Only marginal vertical changes within the profile are evident for the most parameters (Figure 13). The texture is clayey sand (St2) with a slight increase of clay content with depth. The sand fraction is dominated by medium and fine sand. Compared to the Dystri-Ferralic Arenosols a difference in the sand texture is the higher amount of fine sand, having a mean quotient of medium sand to fine sand of 1.5 whereas the Dystric Arenosols have a mean quotient of 3.

The pH-values are neutral to slightly acid over the entire profile. The organic carbon reaches 0.58 % in the topsoil and shows only a slight decrease with depth. In combination with the dark colour of the profile this indicates a deep accumulation of organic matter by bioturbation or a colluvial genesis of the profile. In all horizons the electrical conductivity (EC) is very low (around 20 µS cm^{-1}). Compared to profiles in pure dune sands, this profile exhibits higher total element contents which results in only slightly increased values of the total base reserve (TRB). Due to the higher amounts of clay, humus and the increased pH-values the CEC of the Eutri-Ferralic Arenosols have substantially increased to values of 30-45 $mmol_c$ kg^{-1} compared to the Dystric Arenosols. The concentrations of water soluble ions are low (total 6-14 $mmol_c$ kg^{-1}) with the highest values occurring in the subsoil.

In summary, these profiles also describe extremely nutrient poor soils. Nevertheless, due to a more suitable nutrient status and slightly enlarged field capacity compared to the dune sites, these soils are preferably utilised for the establishment of arable fields.

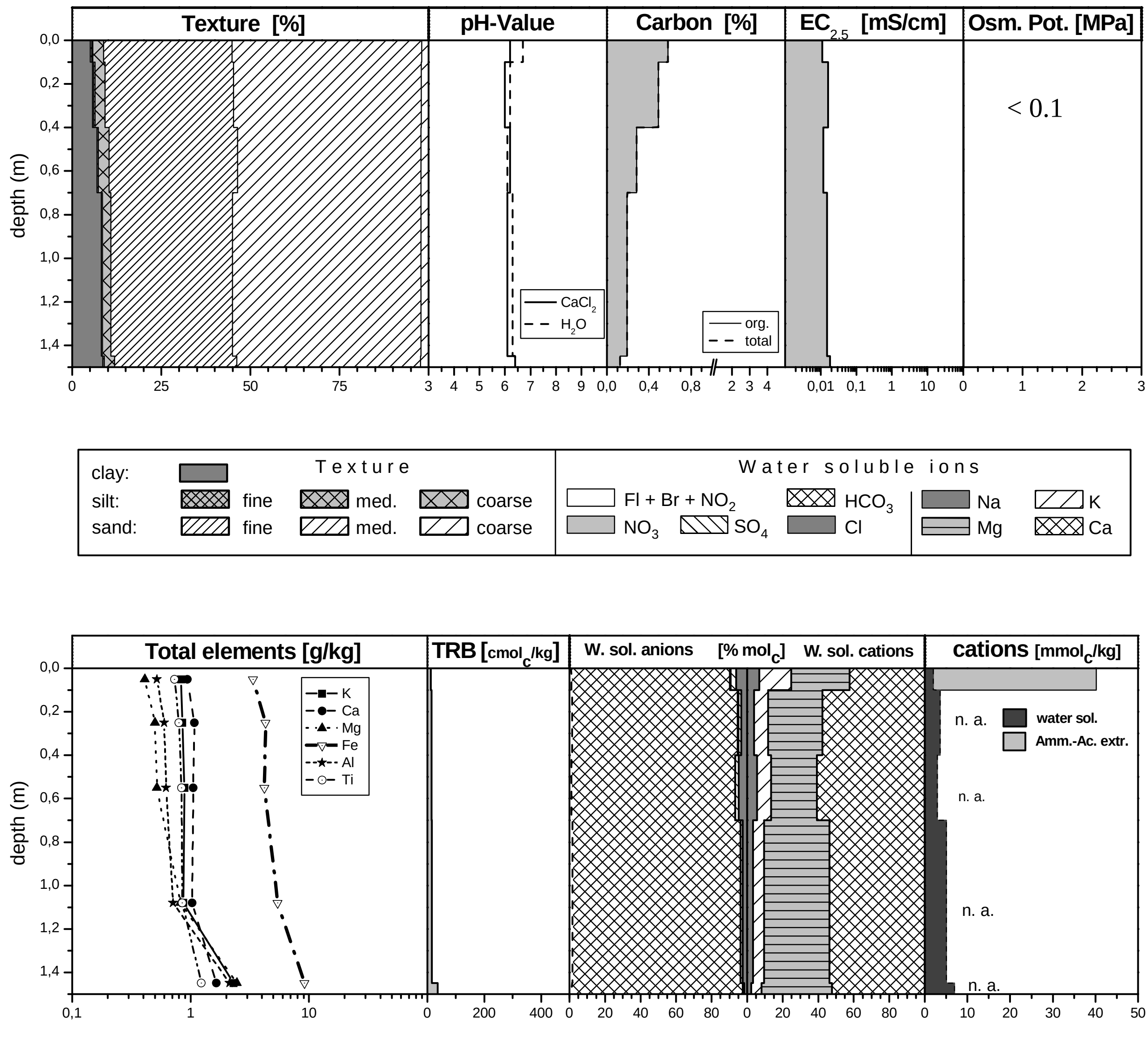


Figure 13 Properties of profile 105

3.1.3.4 Discussion of soil properties

Both observatories inhabit a relatively low variability in soil properties. This is true for both, the differences between the soil profiles and the vertical variations within single profiles. Figure 14 shows the variability of selected soil properties in three different depths intervals. The pH-values and the electric conductivity underline the nutrient poor and acid environment. In Mile 46 the pH-values of the subsoil do not reach the level of Mutompo which is due to fewer samples of deeper profiles in the Eutric Arenosol area. The organic carbon shows a decrease from topsoil to subsoil while the fine fraction of texture (clay & silt) is constantly low over the depth. Only the slight loamy Eutric Arenosols in Mutompo show higher values over the entire profile. The rooting space (RS) is 100 % in all selected profiles, here no limitations or variations within the observatories occur. In general, variations are small as indicated by narrow ranges and small boxes. Only ph-values and organic carbon show variations which can assigned mainly to the ‘dunes’ with lowest values and ‘interdunes’ with highest values. This means also that variations occur mainly on the habitat-scale. To summarise, both observatories are comparable to their soil properties.

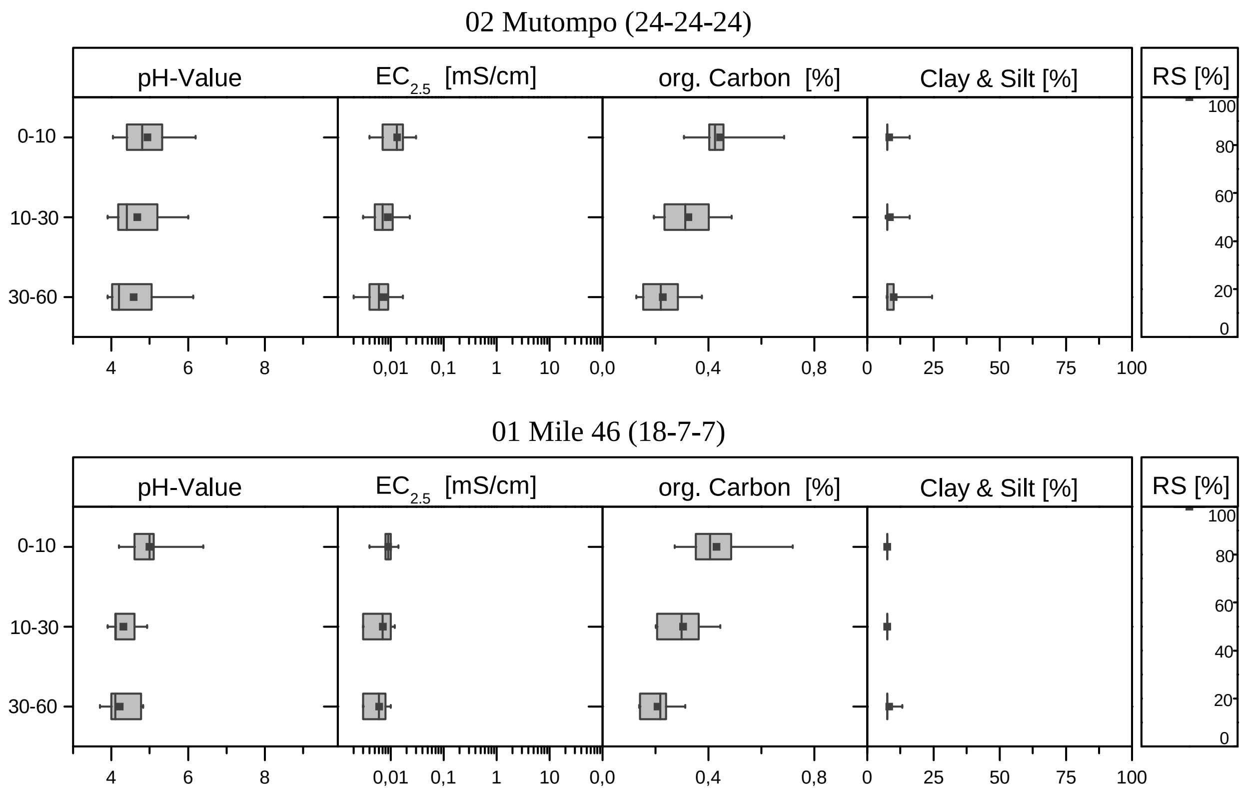


Figure 14 Variability of selected soil properties in three depth intervals for the observatories #01 and #02

Box =25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top→ down), RS= rooting space

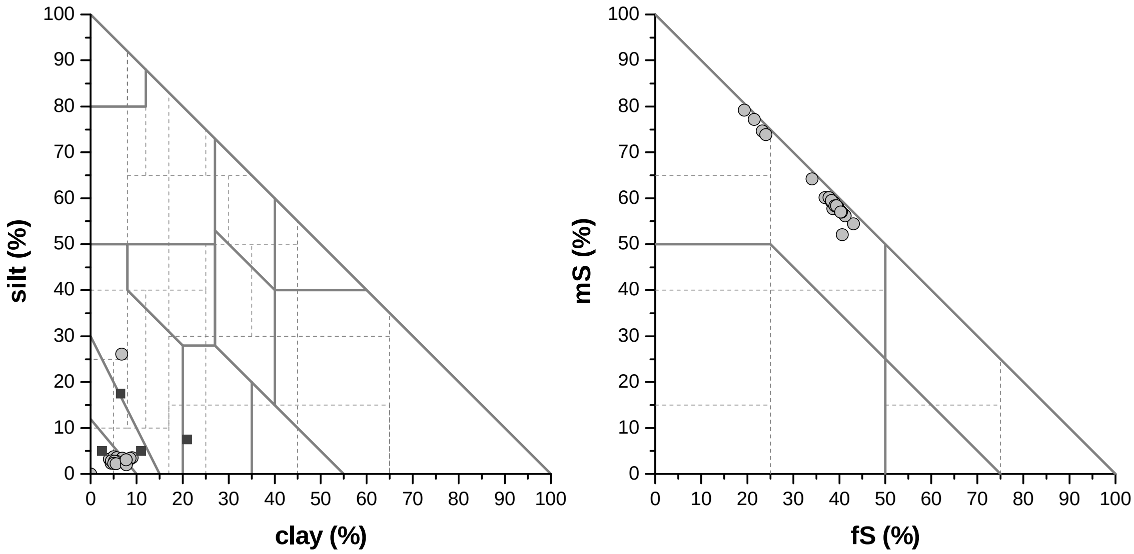


Figure 15 Results of the texture analyses for the observatory #02 Mutompo

squares = finger test (all samples); circles = lab analyses (selected samples)

Figure 15 shows the results of the texture analyses of all samples for the observatory #02. The sandy character is dominant, only few subsoil samples of the Eutri-Ferralic Arenosols show loamier textures. Based on the sand fractions the analysed samples can be subdivided into two clusters. The first cluster with fine sand contents < 25 % consists of samples from the Dystri-Ferralic Arenosols whereas the second cluster with fS > 30 % comes exclusively from samples of the Eutri-Ferralic Arenosols. This striking difference is an additional indicator for the different genesis of the substrates.

Similarities are found in the patterns of soil distribution and units of broader vegetation. Whereas the *Burkeo-Pterocarpetea* is restricted to the Dystric Arenosols on deep, nutrient-poor sands with low pH-values, the *Acacietea* is mainly found on the slightly finer textured and nutrient richer Eutric Arenosols of the omirimbi and their surrounding. We assume that these differences are mainly driven by water supply. The assumption is based on the theory that finer textured soils underlie a higher capillary rise and loss of soil water from deeper horizons by evaporation (see excurse in chapter 3.2).

Although both soil units of this study area consist mainly of sand, the small amount of clay and also the higher amount of fine sand in the Eutric Arenosols results in a finer pore structure in the *Acacietea* favouring faster evaporation. Moreover, the high intensities of rainfall events make run-off more likely than on the pure sands. The percolation and the water storage reach deeper in pure sands which also may affect the vegetation pattern by providing soil water in different depths.

The fact that the sandy soils are leached and are very poor in nutrients as well as their capacity to store nutrients, agricultural utilisation also has to take these aspects into account. The loamier substrates, in general classified as Eutric Arenosols, provide more nutrients and if situated at dune bases or dune streets they also may have a better water supply due to runoff or lateral flow. Regarding the restricted rooting depth of the crops and the short time of the growing season the loamy soils in the study area are thus more suitable for cropping.

To summarise, the slightly loamier Eutric Arenosols, although also a nutrient poor soil, provide a better nutrient supply in comparison to the Dystric Arenosols. This is probably an additional factor for the differentiation of the vegetation structure. Further investigations on the nutrient requirements of the different associations are necessary for the clarification of this hypothesis.

3.2 Observatory 03 (Sonop)

3.2.1 Regional overview

The observatory #03 (Sonop) is situated in the Grootfontein District, Otjozondjupa Region, 120 km north east of Grootfontein on the agricultural research Farm Sonop 903. The farm covers an area of approximately 11.000 hectares. The rainfall of approx. 500 mm a^{-1} is precipitating during the summer months from September until April. Mean annual temperature is around 20°C. The region belongs to the north eastern Kalahari Woodlands (MENDELSOHN et al. 2002) characterised by a mosaic of dry forests and more open savanna vegetation.

Geologically, the region belongs to the Kalahari group characterised by quaternary sediments, i.e. undifferentiated, unconsolidated sands and firm to massive calcretes. Prominent feature of the landscape are the E-W trending longitudinal dunes which were formed during the last glacial period some 16,000 to 20,000 years ago (SCHNEIDER 2004). A large high pressure cell was circulating over the subcontinent for long periods of time and formed the dunes which were likely to be vegetated and stable in the following time period until today. The topography of the area is regularly undulated by the east/west trending dune system. Major landforms are dunes, interdunes (narrow longitudinal, relatively flat surfaces between dunes, locally known as ‘dune streets’), sandplains and depressions (‘pans’). The orientation of the dunes is approximately 280°, with wide flat tops. Differences in height between dunes and interdunal streets are ca. 20 m (see Figure 16), the mean distance between the dunes is around 1.5 – 2 km. In comparison to the observatories #01/#02 a clear distinction of dunes and interdunal streets is visible by topography as well as by vegetation structure. Interdunal streets or “dune valleys” are often rather open bush- or grasslands with shrub savanna elements whereas the dunes are approximating an open tree savanna.

Most important land-use in the region and also on the research farm is cattle farming in fenced camp systems and to some extent pasture or crop production. The cropping areas are normally situated within the interdunal streets clearly visible on satellite images. The most important pressures on the environment are the clearing of natural vegetation for crop cultivation and overgrazing leading to a shift in the natural vegetation (e.g. bush encroachment). Detailed information on the environment of the Sonop Research Station is provided in the soil study of KUTUAHUPIRA et al. (2001).

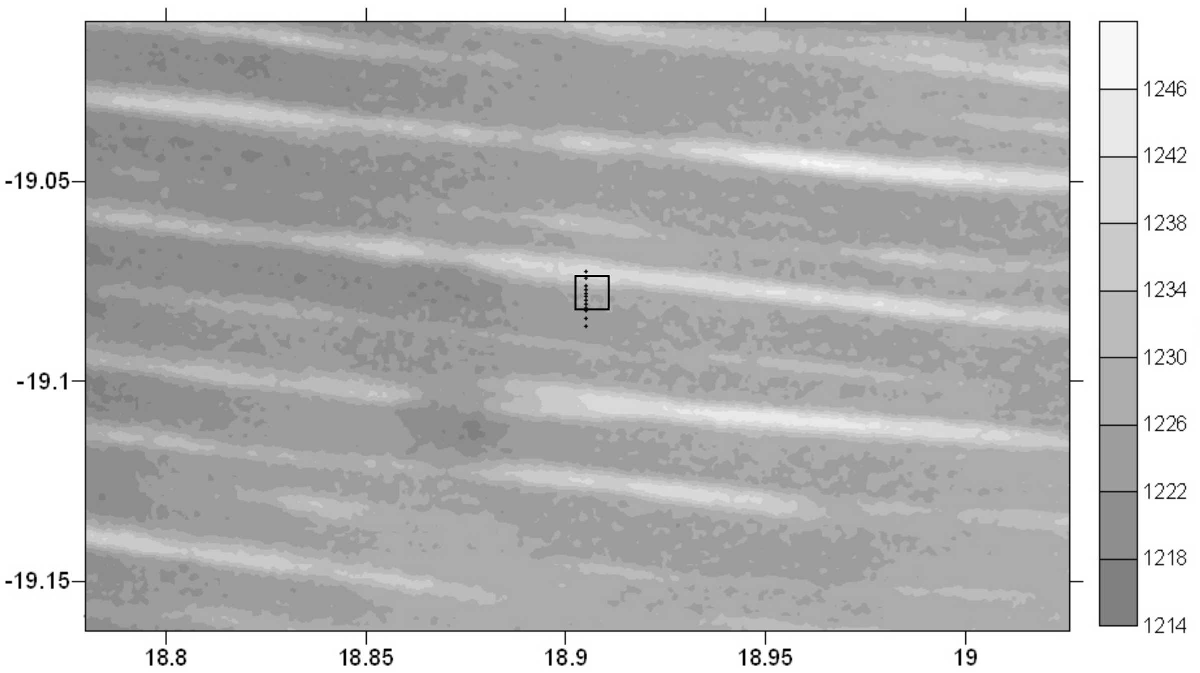


Figure 16 Elevation model by SRTM (Shuttle Radar Topography Mission) data (ca. 12 x 20 km) of the area around Sonop observatory (legend in m asl). The sampling positions are marked.

3.2.2 Observatory description

The observatory #03 (Sonop) is situated in a transition zone between an interdunal street and a dune. In Figure 17 the position in the landscape and a digital elevation model of the observatory illustrate the two main landforms dune and interdune. As the system is very wide with dunes of 1 km width and interdunal corridors with distances across up to 2 km, the observatory does not include the crest of the selected dune. The heights increase from the dune foot with ca. 1220 m to 1238 m asl over a distance of 600 m. Especially in the transition zone between the dune foot and the interdune few micro pan features are visible being the lowest points in the system and waterlogged for a short time of each year. They are comparable to the origin of the ‘omuramba’ system as described in the observatory #02 (Mutompo).

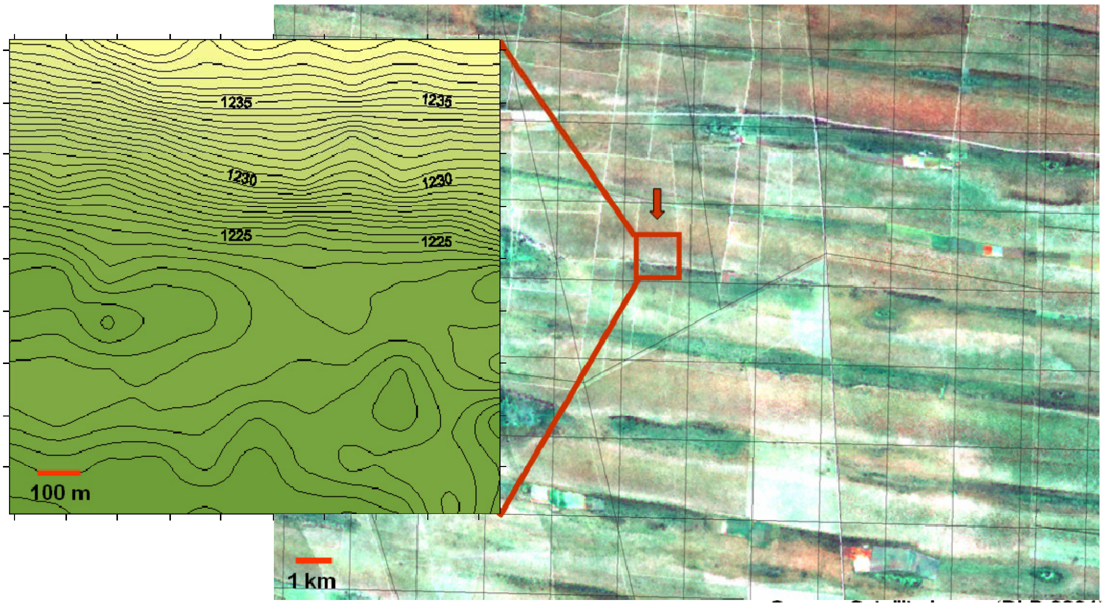


Figure 17 Location of the observatory #03 (Sonop) and topographic situation

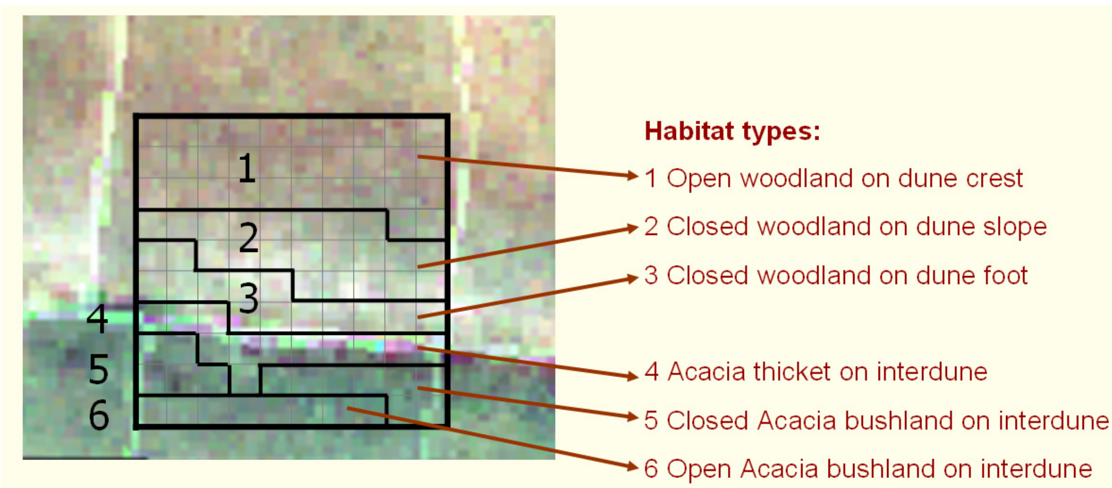


Figure 18 Distribution of habitat types in observatory #03 (Sonop)

Due to the clear correlation between topography and vegetation the mapping of habitat types was primarily based on the topography with some additional differentiation in the interdune area by the vegetation structure. The designation and distribution of habitat types are shown in Figure 18 with an underlying LANDSAT image that points out the analogue linear pattern of the natural structures. Bright linear structures parallel and perpendicular to the dunes are fence lines with adjacent control paths. Similar to the observatory #02 (Mutompo), the densest Acacia thicket (habitat 4) is associated with micro pan features in the transition zone between dune foot and interdune. The different aspects of the vegetation structure are clearly reflected by the colours in the satellite images showing woodland savanna elements in a pale to red trend and shrub and thicket savanna habitats with green and violet colours.

3.2.3 Soils

3.2.3.1 Main soil units

The soil units of the observatory #03 (Sonop) and their frequency distribution are shown in Figure 19. Differing from the standardised ranking procedure this observatory is surveyed by a north/south transect analysis. This was carried out to cover all habitats in the linear landscape system with a reduced number of hectare sites due to the lower priority of this observatory in the BIOTA South framework In accordance with the vegetation analysis the transect was elongated for 200 m to the north and 400 m to the south to cover possible changes within the interdune and towards the dune top. As all habitats were covered by this modified procedure the resulting variety of soil units can be regarded as comparable to the standardised procedure.

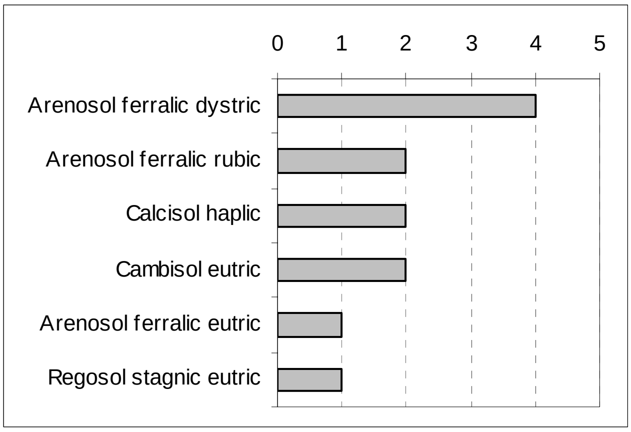


Figure 19 Frequency distribution of WRB (FAO 1998) soil units in observatory #03 (Sonop)

All profiles within the three dune habitats are classified as Ferralic Arenosols. This is due to the low CEC of the sandy substrate with low contents of organic carbon. They consist of deep sand, are well drained and show little differentiation over the profile depth of 2 m. A distinction could be found in Rubi-Ferralic Arenosols (Dystric) in the northern part of the transect which cover the upper dune part with more reddish substrates and Dystri-Ferralic Arenosols on the dune slope and the dune base with more pale sands.

A unique soil unit is the Eutri-Stagnic Regosol which occurs in the micro pans along the interdunal streets between the Calcisol / Cambisol association and the Arenosols of the dune habitats. These soils consist of deep loamy sand to loam and are very distinct from the surrounding substrates. There are no signs of fluvial deposition. Prominent mottles of iron oxides indicate seasonal water logging. Also the lab analyses reveal a significant part of oxalate-extractable iron which is an indicator for ongoing hydromorphologic dynamics and led to the stagnic qualification.

In the adjacent interdune habitats to the south, the soils show distinct colours and structures. Here, the common units are Haplic Calcisols and Eutric Cambisols. Both units display very similar soil properties; their distinction depends on the depth of the underlying calcretes or petrocalcic horizon regularly found in the interdune area. Compared to the dune habitats darker and greyer substrate colours occur, the structure is harder and the soils have a loamier texture.

At the southern end of the transect, a Eutri-Ferralic Arenosol occurs which is developed in a shallow dune substrate with intergrade to the interdune substrate. This intergrade is indicated by slightly higher clay and silt content as well as higher organic carbon contents.

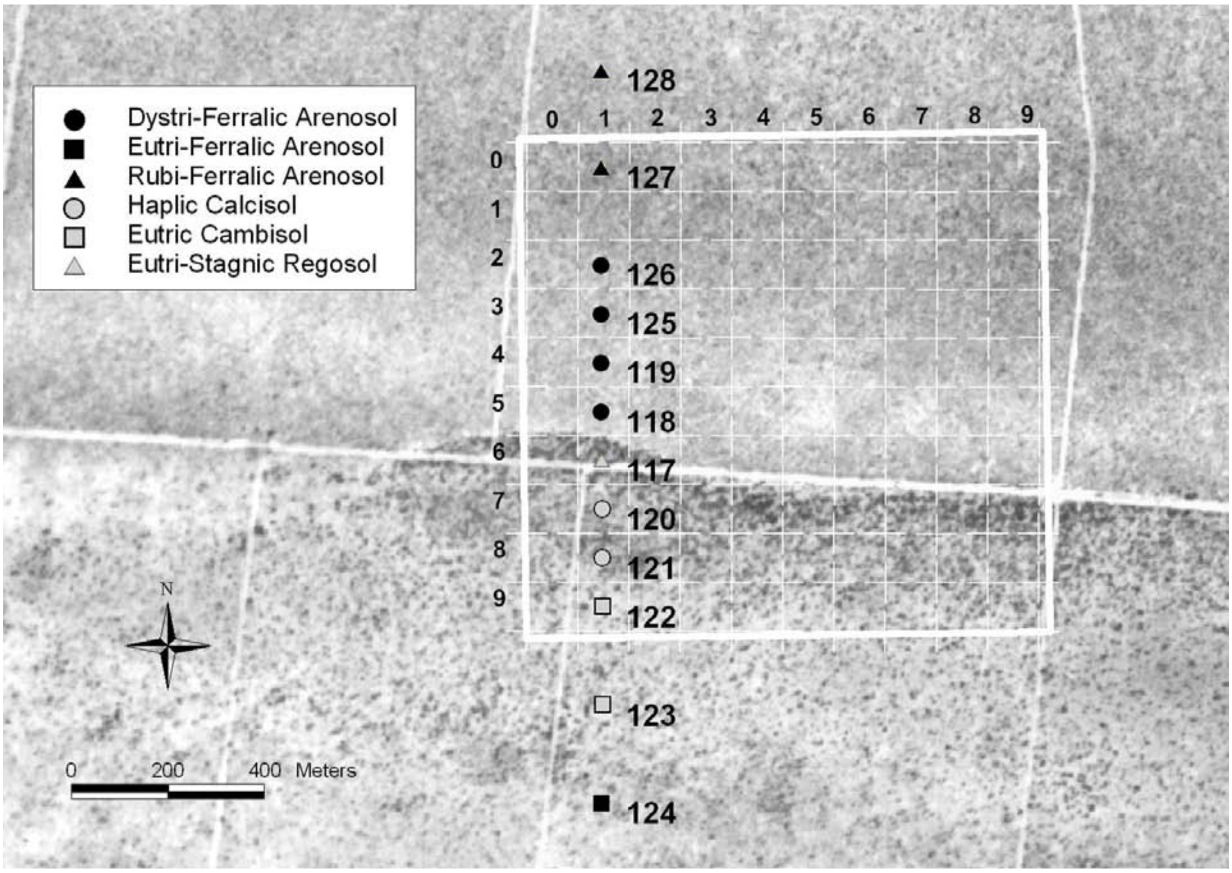


Figure 20 Distribution of soil units (WRB 1998, 2nd qualifier level) along the transect on the obs. #03 Sonop with ha-grid, position and number of soil profiles on aerial photograph

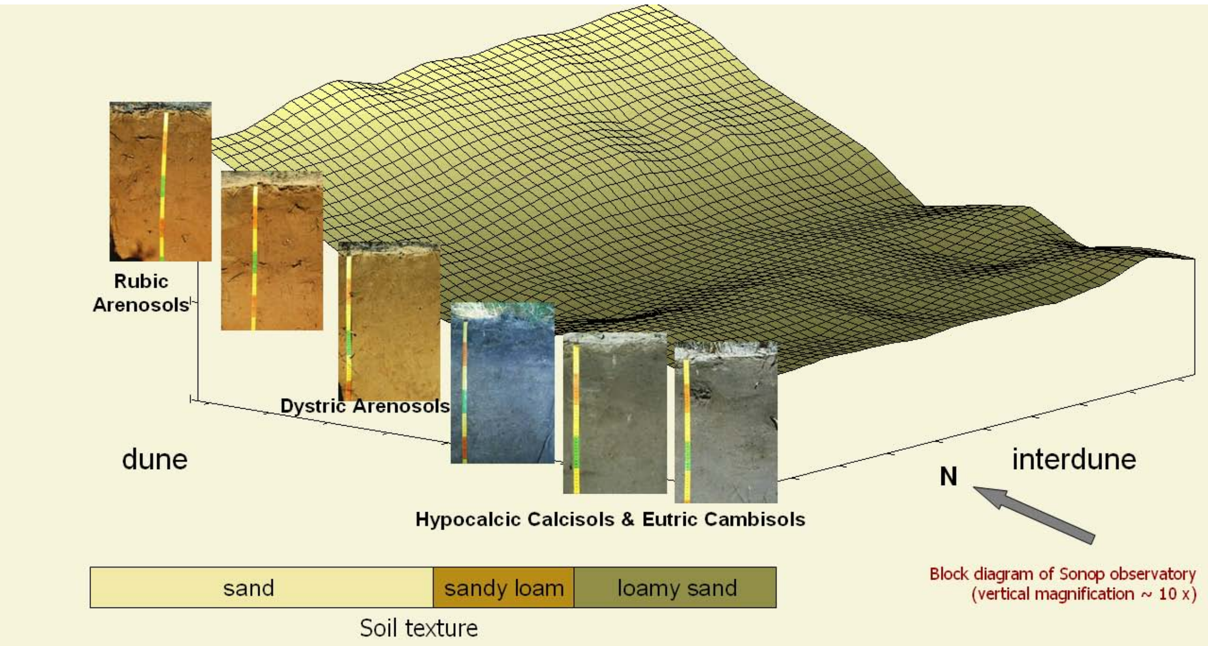


Figure 21 DEM of the observatory Sonop with soil transect

3.2.3.2 Remarks on classification

The classification of the soil units was based on the WRB (1998) nomenclature. Although a maximum of three qualifiers for single profiles is possible, no differentiation above the two-qualifier level was needed. The assigned qualifiers and reference groups were sufficient to delineate the most important soil features (texture, low CEC, base saturation, calcretes and pH-value) and differentiate various soil units. The classification of the Arenosols and Calcisols is explicit due to texture and calcic requirements whereas the classification of the Cambisols allows some space for interpretation. These profiles show no clear features for in situ structural development, the homogenous dark colour could also be a result of a colluvial development. It was decided that the Cambisol is the most feasible option to express the loamier components of these soils compared to the other option Regosol which is much more unspecific. In comparison to the interdune soils of the observatories #01 and #02 the higher clay content is sufficient for a sandy loam texture allowing the definition of a cambic horizon while the specific character of the texture, a clayey sand with low silt contents, cannot be stated for certain. The finer texture classes of the German soil classification (AG BODEN 1994) allow the separation of these specific cases and were therefore additionally used in the description of the reference profiles.

The application of the new version of the WRB (2006) reveals only minor changes. The new introduced qualifier “clayic” now allows expressing the high clay component in the subsoil of the Eutri-Stagnic Regosol (→Stagnic Regosol (Eutric, Endoclayic)). In the case of the Rubi-Ferralic Arenosols the ranking of the qualifiers changed to a higher priority of the qualifier “rubic” (→Ferralic Rubic Arenosol).

3.2.3.3 Description of reference profiles

Reference profile # 1

Profile: **122**	Ha: **91**	Classification (WRB 1998) **Eutric Cambisol** (WRB 2006) **Haplic Cambisol (Eutric)**

cm		Accumulation of single bleached sand particles, low penetration resistance (dry), weakly developed biotic crust
20	Ah	Sandy loam (St2) with medium sand (mSfs), single grain structure, brownish-dark grey, Munsell 10YR5/2 dry and 10YR4/1 moist, 11-20 roots/dm², low excavation difficulty
40	Ah2	Sandy loam (St2) with medium sand (mSfs), massive structure, brownish-grey, Munsell 10YR5/2 dry and 10YR4/1 moist, 11-20 roots/dm2, high excavation difficulty
60	B1	Sandy loam (St2) with medium sand (mSfs), massive structure, brownish-grey, Munsell 10YR5/2 dry and 10YR4/1 moist, 11-20 roots/dm2, high excavation difficulty
85	B2	As above
1,05	B3	Sandy loam (St3) with coarse sand (gSfs), massive structure, brownish-grey, Munsell 2,5YR5/2 dry and 10YR5/2 moist, 11-20 roots/dm2, high excavation difficulty
1,15	B3	loam (Ls3), massive structure, brownish-grey, high excavation difficulty 1,15 m → massive calcrete

Figure 22 Description of profile 122

The Eutric Cambisol of Figure 22 is a typical example for soils developed in the interdune area in deep colluvial sandy loams (> 1 m) and with an underlying calcrete. The texture is dominated by medium and fine sand and shows a significant increase in clay content from 5 % in the topsoil to 25 % in the subsoil (Figure 23). The silt content is low with 5 % across the entire profile. Silt content of the deepest horizon is overestimated by the finger test due to the occurrence of calcium carbonate. The dominant texture in the profile is clayey sand (St2, St3). The German texture classes (AG BODEN 1994) allow specifying this unique texture which often occurs in the savanna and woodland observatories. The soil reaction is slightly acid over the entire profile except for an increase in the contact zone to the calcrete layer.

Mean bulk density is around 1.6 g cm^{-1}. The organic carbon reaches ~ 0.4 % in the topsoil and shows only a slight decrease with depth parallel to a greyish colour in the profile. The contact zone to the calcrete even shows an increase of organic carbon which is probably a sign of a former A-horizon and supports the colluvial genesis theory. C/N Ratios are constant with around 10. The electrical conductivity (EC) is very low with 10 - 30 µS cm^{-1} over the profile but here also an increase in contact with the calcrete is evident. This may be the effect of the calcium carbonate and an accumulation of translocated ions in the profile due to the barrier effect of the calcrete preventing a deeper drainage. Total element contents and TRB increase with profile depth with an abnormal peak in the fourth horizon. Whereas the normal trend follows the clay content (except calcium which increases with the calcrete contact) a maximum in the depth of 60-85 cm occurs. This might also be an effect of colluvial genesis aspects. However, other signs of stratification are not detectable. Pedogenic iron (not shown in graph) amounts to only 10 % of the total iron content which indicates a relatively low weathering status. The contents of water soluble ions are very low with 3 - 5 $mmol_c$ kg^{-1}. The CEC of the substrates (not shown in Figure 23) is in the range of 40 to 80 $mmol_c$ kg^{-1}.

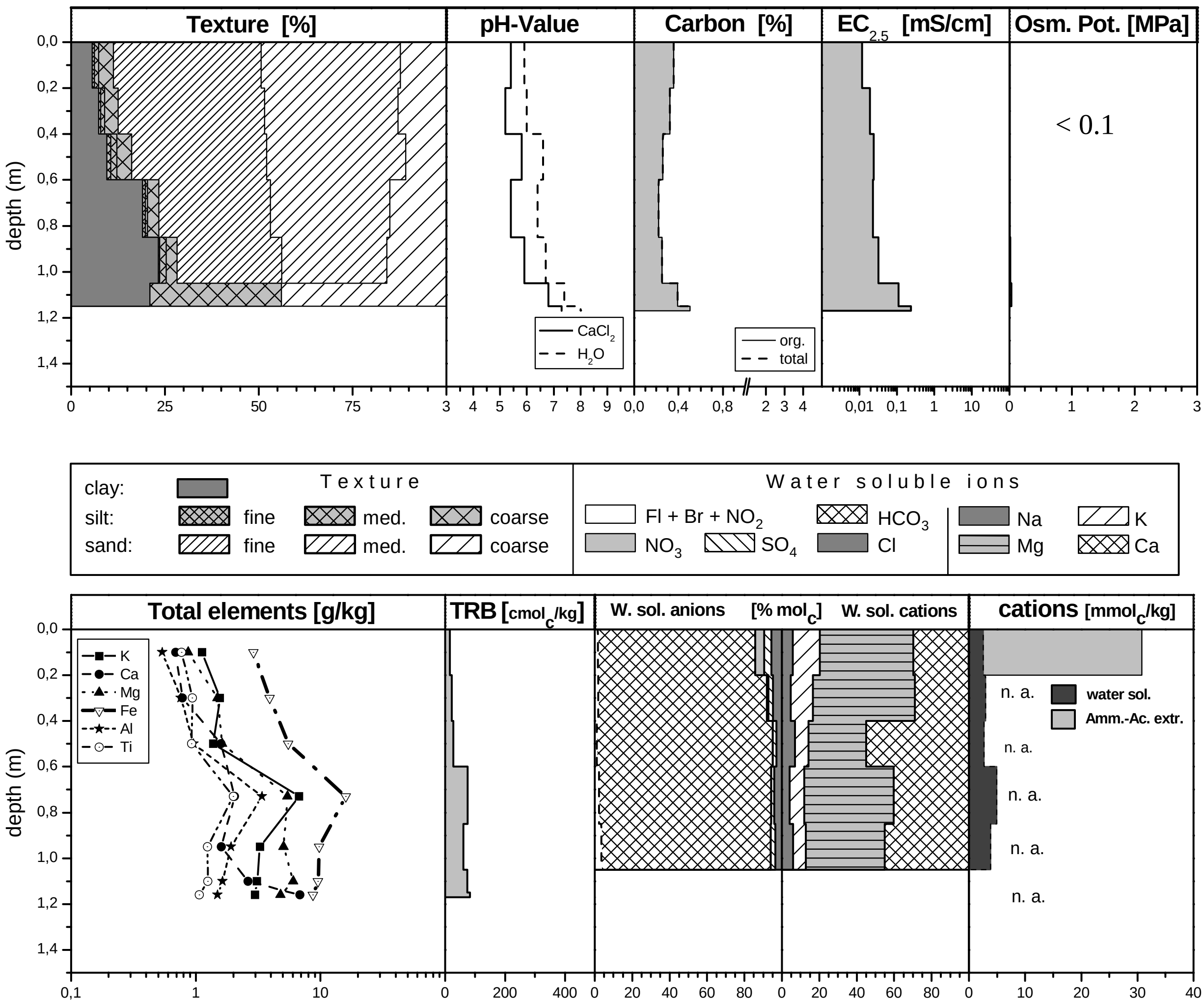


Figure 23 Properties of profile 122

Reference profile # 2

Profile: **128**	Ha: **-**	Classification (WRB 1998)	**Rubi-Ferralic Arenosol (Dystric)**
		(WRB 2006)	**Ferralic Rubic Arenosol (Dystric)**

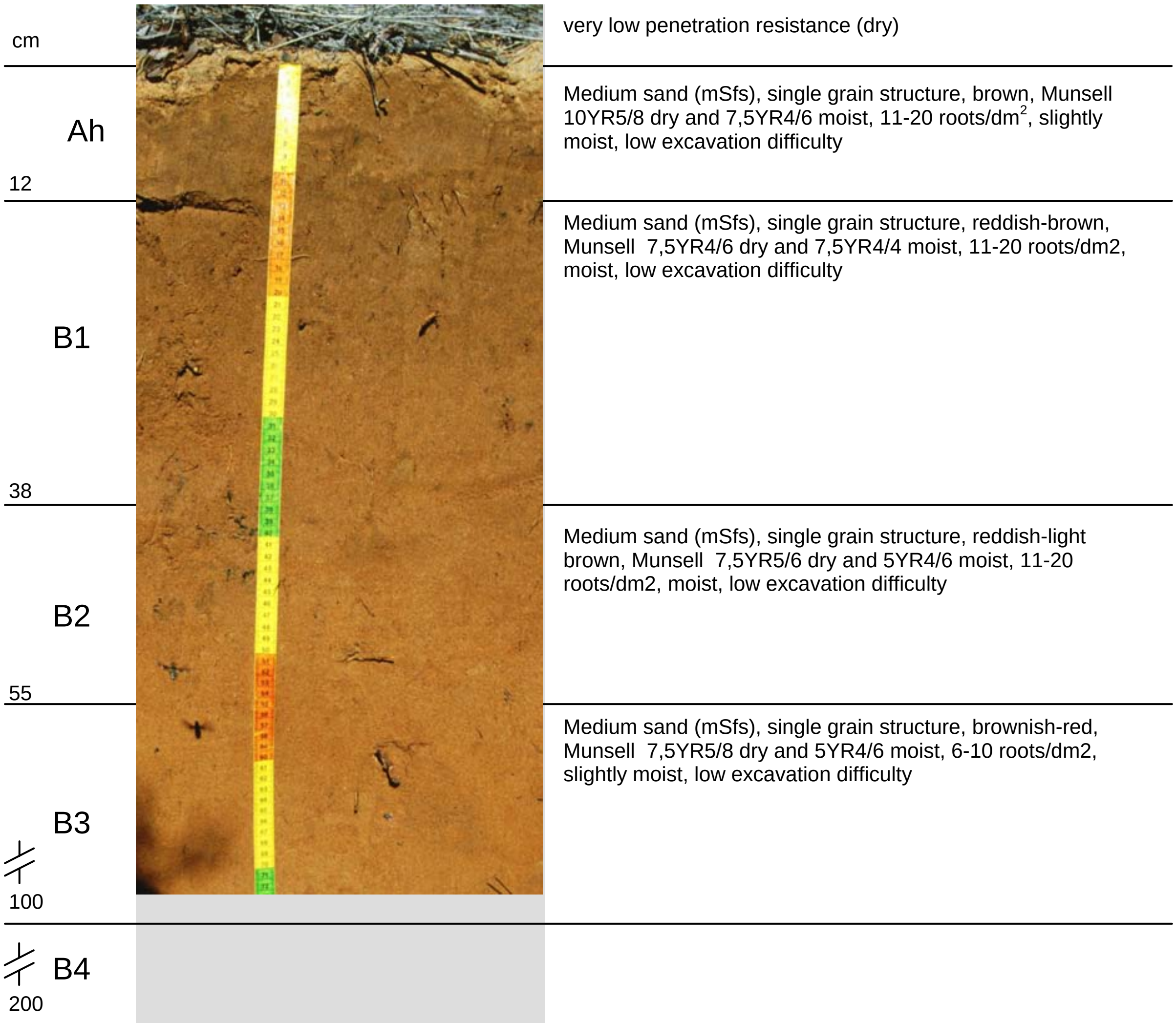


Figure 24 Description of profile 128

The Rubi-Ferralic Arenosol of Figure 24 is a typical example for soils developed in the upper dune parts with deep, reddish pure sands. Except for the colour they also represent the properties of the paler Arenosols in the dune slopes. Texture is dominated by medium sand with a slight increase of the fine sand proportion with depth (Figure 25). Mean bulk density is around 1.7 g cm^{-1} and the pH values are very strongly acid. The organic carbon reaches only 0.23 % in the topsoil and shows a considerable decrease with depth. C/N Ratios are constant with approx. 11. The EC is very low with 7 - 15 µS cm^{-1} across the entire profile. According to the quartz dominated nature of the substrate, the total element contents and TRB are very low across all horizons (Mg < 0.1 g kg^{-1} in all horizons). Within the elements presented, the concentration of total iron is largest and more than 80 % of this has a pedogenic origin (iron oxides) which causes the reddish colour. The content of water soluble ions is extremely low (1 - 2 $mmol_c\ kg^{-1}$). The CEC (not shown in the Figure 25) is between 6 and 9 $mmol_c\ kg^{-1}$.

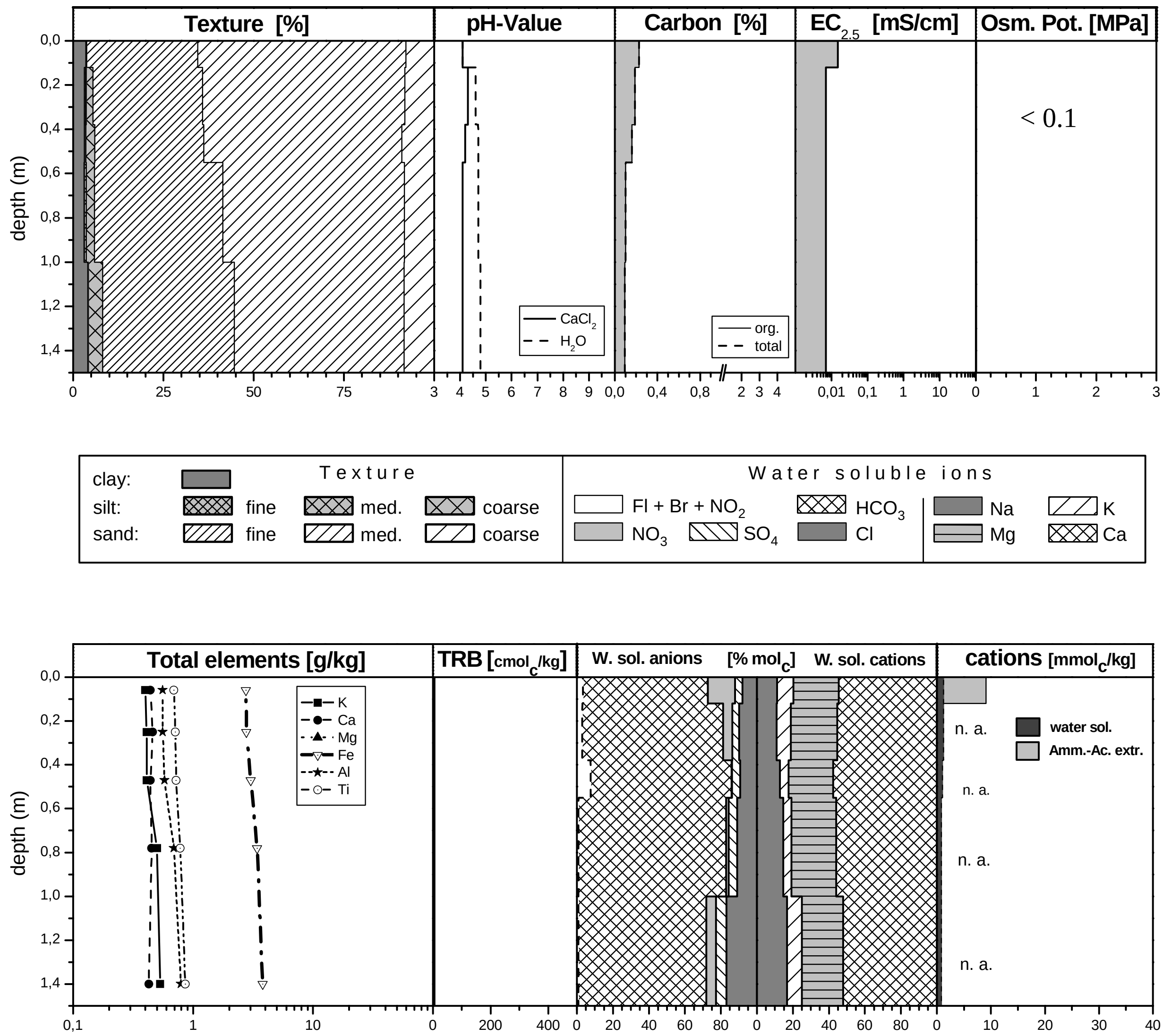


Figure 25 Properties of profile 128

3.2.3.4 Discussion of soil properties

In this observatory the variability of soil properties is mainly defined by the two reference profiles described. For all parameters shown in Figure 26 the lower values represent the Arenosols and the higher values the Cambi- and Calcisols. The short whiskers of the pH values indicate the "aggregated" character of this parameter. Vertical differences in the profiles are also of minor importance, except for organic carbon. The only parameter with an uneven distribution is the clay and silt content which shows higher ranges due to the single pan profile with high clay contents. The rooting space (RS) is nearly 100 %, only in two Calcisols a small restriction occurs.

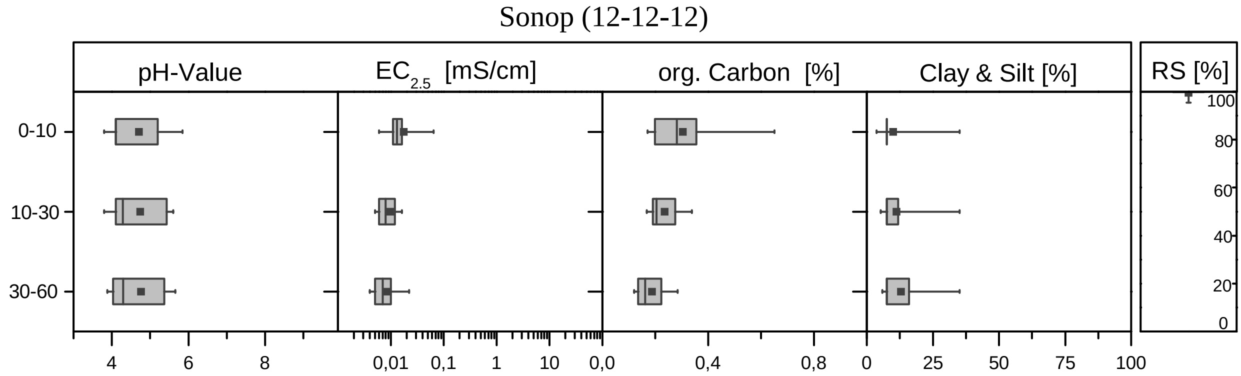


Figure 26 Variability of selected soil properties in three depth intervals for the observatory #03

Box =25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS= rooting space

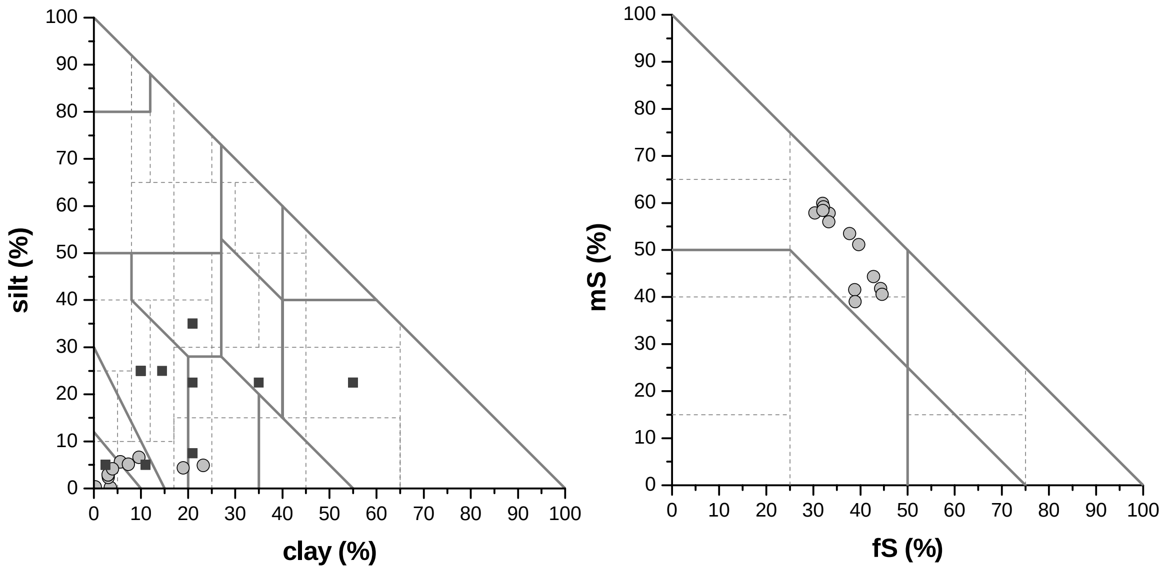


Figure 27 Results of the texture analyses for the observatory #03 Sonop

squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 27 shows the results of the texture analyses of all samples for the observatory #03. The sandy and clayey sandy character is dominant, only few samples of the Stagnic Regosol show loamier textures (finger tests). With respect to the sand fraction the analysed samples can be subdivided into three clusters. The first cluster shows medium sand percentages > 55 and consists of samples from the Rubi-Ferralic Arenosols (in the pure sand) of different depth. The second cluster originates from samples of the loamier interdune soils smaller medium sand (< 46 %) and therefore higher fine sand contents. The two samples between the clusters belong to the deepest subsoil horizons of the dune profiles. The differences are not very strong but can be interpreted as a further hint for the different origin and/or genesis of the substrates.

The transition from the central Namibian thornbush savanna to the northern Namibian woodland savanna is reflected by a banded vegetation pattern which clearly reflects the soil properties in this observatory. The drier thornbush savanna elements are restricted to the loamier and shallower interdune soils whereas the woodland savanna is found on the sandy dunes. Main factor for this differentiation seems to be the water supply which is mainly driven by the soil texture (see excursus “water availability and evaporation”).

EXCURSUS: Water availability and evaporation under arid and semi-aridconditions

Sandy soil profiles are normally interpreted to have a low water holding capacity. This is true, if one considers the classical interpretation of soil physical properties and the available estimates and measures for texture classes. However, i) often the water holding capacity of especially medium and fine sand is only little less compared to loamy sand and ii) infiltration rates on sandy substrates are higher. The latter is important as the erratic nature of the rainfall often leads to runoff processes. Additionally, the high potential evaporation in arid and semi-arid areas of Namibia with 1800 -3500 mm / year (MENDELSOHN et al. 2002) extricates the water rapidly out of the soil. Finer textured soils show a disadvantage under these conditions because they underlie a higher capillary rise of soil water from deeper horizons. The drying of finer textured soil is therefore often faster and reaches deeper than in a more sandy texture. These aspects are summarised in the "inverse texture hypothesis" saying that under arid or semi-arid climates with high potential evaporation rates more sandy soils provide a better protection against evaporation than loamier soils and thus have a higher biomass production by the natural flora. This theory was initialised by NOY-MEIR (1973) and strengthened by studies in different regions (e.g. SALA et al. 1988, SCHOLES & WALKER 1993, FERNANDEZ-ILLESCAS et al. 2001, LAIO et al. 2001, RODRIGUEZ-ITURBE and PORPORATO 2004). To confirm this theory a comparison of an Arenosol and a neighbouring Cambisol on the observatory Sonop was done by the BIOTA subproject S06 (Botany, Ben Strohbach, unpublished data). Soil moisture measurements with gypsum blocks were established in the typical dune and interdune soils as they are described as reference profiles for the observatory #03 Sonop.

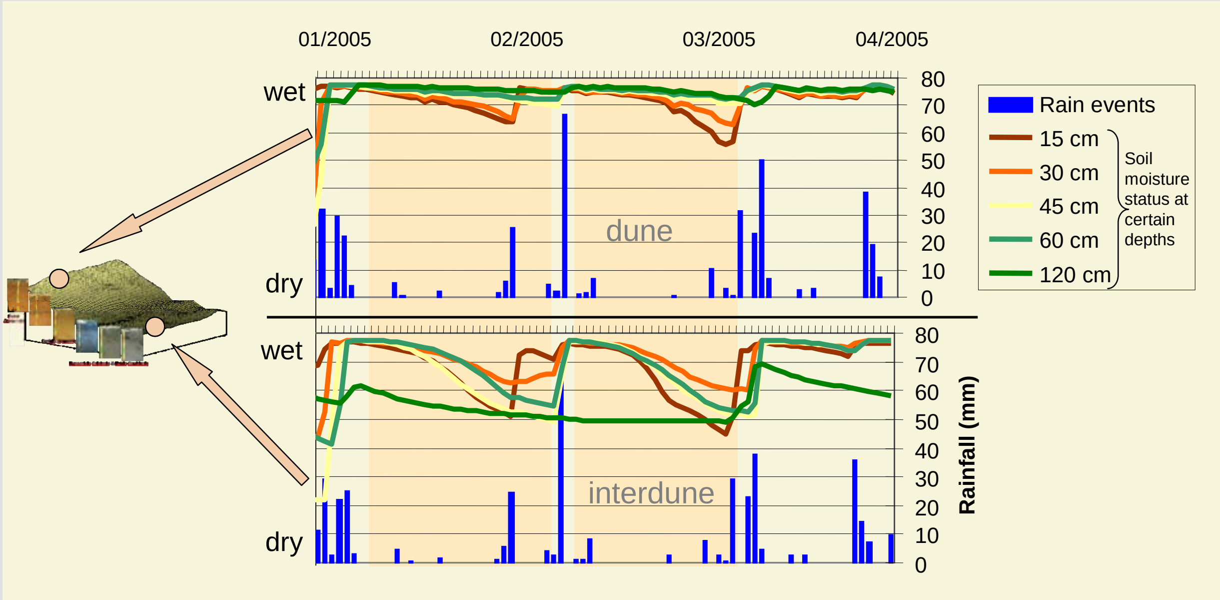


Figure 28 Soil moisture behaviour of two different sites over the rainy season 2005 (data by B. STROHBACH, unpublished)

Figure 28 shows the results of the two measured sites from the rain season 2005 by a period of four months. The simple technique of gypsum blocks does not allow a precise interpretation of the soil moisture content and tension but is sufficient to illustrate the "inverse texture" effect. The coloured lines indicate the moisture status at the certain depths. There are two significant drying cycles after the rain events that show the faster drying of the loamier interdune site.

However, the mechanisms behind this result are complex. The scheme in Figure 29 shall illustrate the combination of different effects which leads to the drier condition in the interdune site. Given the assumption that both sites receive the same amount of rain, the water in the interdune does not infiltrate as deep as on the dune sands, due to a higher storage capacity. The loamy sand also has higher retention of non plant available water. Finally the finer texture enhances evaporative loss of water. As a result, the amount of plant available water is lower in the interdune and the storage is nearer to the surface. Both factors (evaporation and residual water) lead to a distinct water supply and by this to distinct vegetation units. It can be summarised as drier conditions in the interdune due to the loamier soil texture. From this example we can conclude that even small differences in soil texture – from sand to loamy sand is an increase of 10 % clay and silt – act as a strong modifier for the plant available water. In addition to this evaporation and storage effects also run-off on the loamier topsoils, which are vulnerable for crusting, may increase the water deficit. However, this example requires further measurements as the potential difference in the transpiration of the two sites are not yet measured.

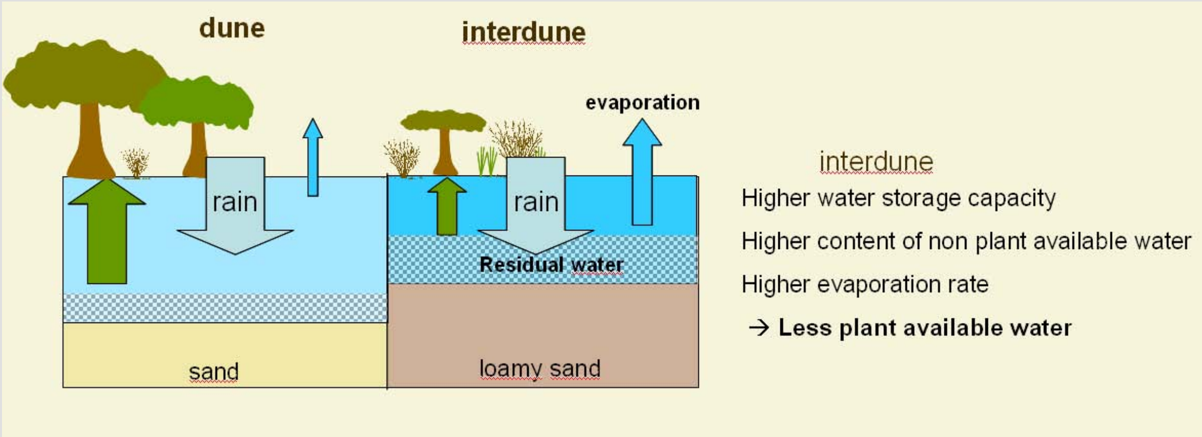


Figure 29 Scheme of soil water dynamics in the dune / interdune system

Generally the inverse texture hypothesis is valid for all arid and semi-arid sites along the transect. It is therefore an important point for the understanding of vegetation patterns in this study.

3.3 Observatory 04 Omatako (Toggekry)

3.3.1 Regional overview

The observatory #04 (Toggekry, commonly named Omatako) is situated approx. 50 km north of Okahandja in the region Otjozontjupa on the Farm "Omatako Ranch" which covers an area of around 15,000 ha. During the summer months (Sept.-April) approx. 360 mm of rainfall precipitates which is very variable in space and time. Mean annual temperature is around 20 °C. Potential evaporation rates are 1,800 – 2,000 mm a^{-1}. The potential natural vegetation is an open thornbush savanna with *Acacia* species as main woody components and grasses like *Stipagrostis uniplumis, Aristida* and *Eragrostis* species in the herb layer. In some spots, bush encroachment by *Acacia mellifera* can be observed.

Geologically, the region is situated in a transition zone between the western Kalahari margins towards the east and the escarpment in the Damara belt with the Damara supergroup (schists, dolomites) and Damara granite intrusions in the west. The drainage system is heading towards the north, to the margins of the Omatako catchment.

The topography of the area is almost flat to gently undulated with a mean height of 1500 m asl. Major landforms are plains and in smaller portions riviers, pans and few rocky outcrops. Important micro-features are the mounds of the termite *Macrotermes michaelseni*.

Extensive cattle and game farming are the dominant land-use systems in the area and on the farm. The most important pressure on the environment is overgrazing leading to a shift in the natural vegetation (e.g. bush encroachment).

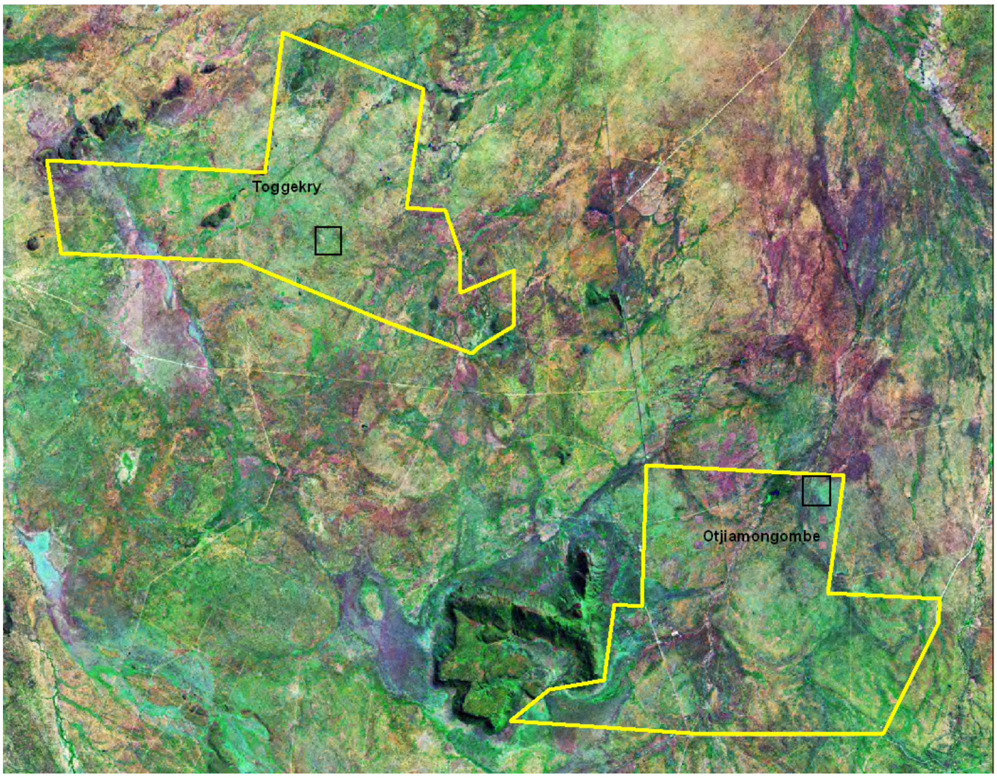


Figure 30 Satellite picture of the region around the observatories #04 (Omatako) and #05 (Otjiamongombe) with marked farm border (Landsat TM image © Nasa)

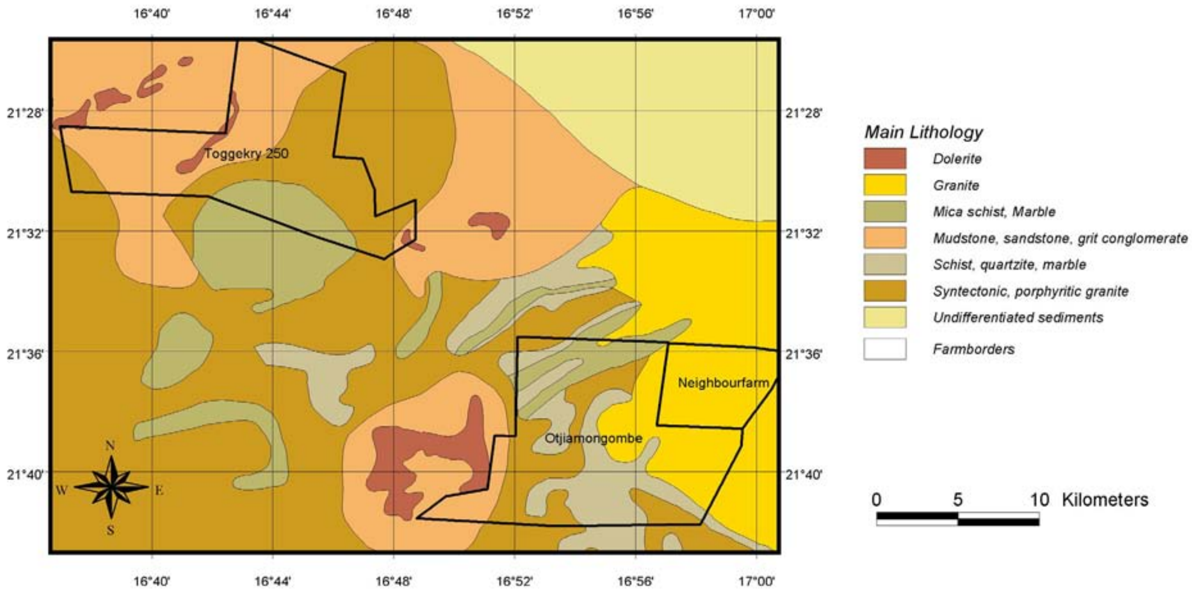


Figure 31 Extract of the geological map 1:250,000 (Okahandja) of the region around the observatories #04 (Omatako) and #05 (Otjiamongombe)

3.3.2 Observatory description

The observatory itself is situated in the central part of the farm. The topography is flat with a mean height of 1522 m asl, 6 m total variation and a slight inclination towards the north. The unconsolidated substrates consist of sandy to loamy textures with different colours from pale brown in the sandier layers to reddish colour in the loamy and clayey materials.

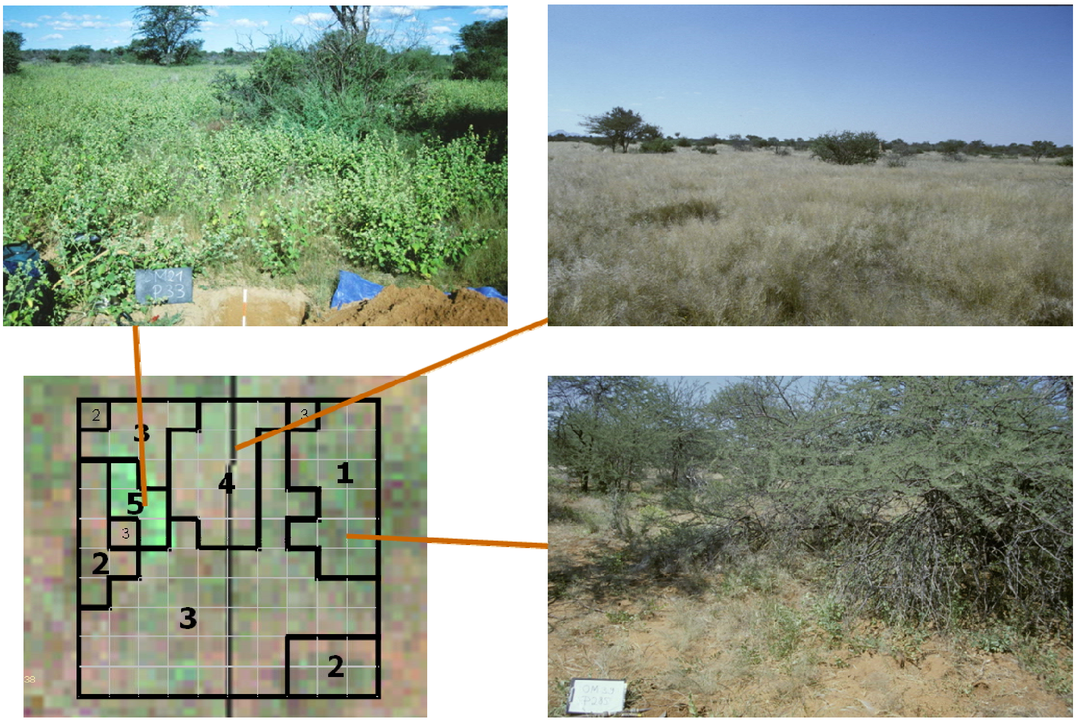


Figure 32 Overview of the habitat types of the observatory #04 (Omatako)

The observatory is not dissected by any rivier, only few erosion features like small gullies indicate surface drainage during the intense rainfall events. Due to analogies in the substrate and vegetation patterns, the habitat types were chosen by both, substrate colour and vegetation structure. The habitat types used and their distribution are shown in Figure 32 with an underlying LANDSAT image.

Habitat 1 and 2 represent plains with red, loamy substrates and a more dense vegetation structure of bushes and trees (higher tree density in habitat 1). Habitat 3 consists of yellow to pale substrates with fewer trees but partly a high density of *Acacia mellifera* patches. An open grass dominated vegetation structure with pale substrates is typical for Habitat 4 whereas Habitat 5 represents a unique situation of sandy substrates with pioneer vegetation such as *Sida cordifolia*, caused by massive disturbances of animals such as aardfark, warthogs and other larger mammals. All habitats are affected by the activity of the mound building termite *Macrotermes michaelseni*.

3.3.3 Soils

3.3.3.1 Main soil units

Differing to the other observatories, 40 soil profiles were examined by standardised ranking procedure. The soils units of the observatory #04 (Omatako) and their distribution are given in Figure 33.

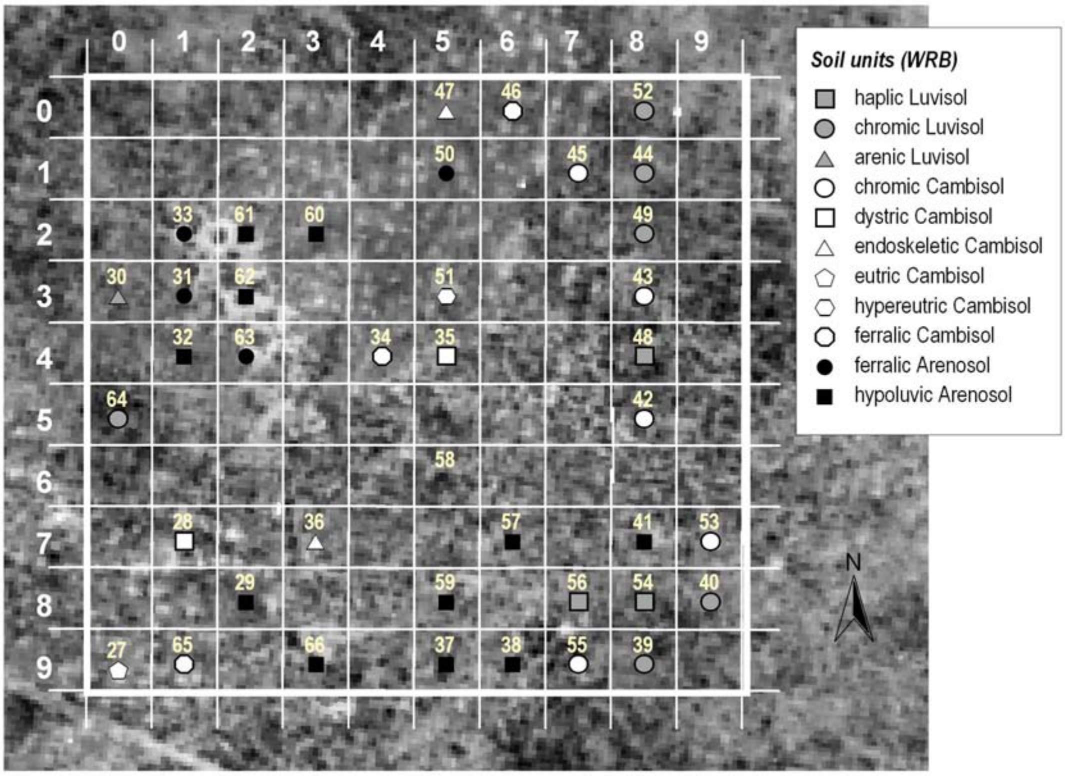


Figure 33 Distribution of soil units (WRB 1998, 1st qualifier level) on the observatory #04

According to the WRB (1998), the reference groups Arenosol, Cambisol and Luvisol are found. In Figure 34 the frequency of the soil units on a two qualifier level of the first 25 ranking priorities is given. Approximately one third of the profiles are Arenosols which are predominantly found in and around the habitat 5 and in some sandier areas in the southern part of the observatory (see Figure 33). A soil unit bridging to the Luvisols is the Hypoluvic Arenosols, showing signs of weak clay enrichment and/or translocation into the subsoil horizons. Luvisols are exclusively found in habitat 1 and 2, here associated with Cambisols which are mostly classified as ‘eutric’. In contrast, the yellowish to pale coloured Cambisols in habitat 3 and 4 are in most cases more sandy and ‘dystric’. In nearly all profiles the rooting depth is larger than 1 m, on few sites limitations caused by saprolitic bedrock occur.

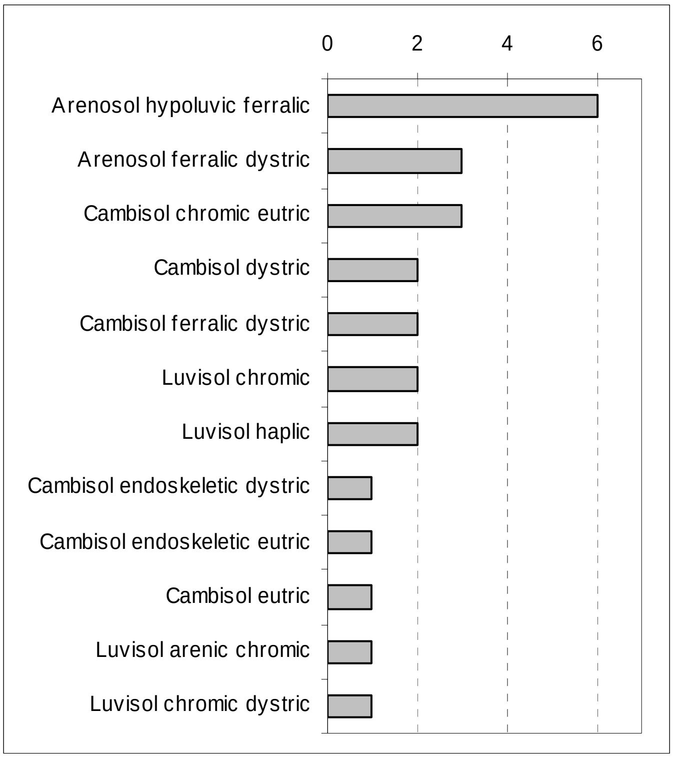


Figure 34 Frequency distribution of WRB soil units in observatory #04 (Omatako)

The most frequent qualifiers eutric, dystric, ferralic, arenic and chromic reflect the variability within the base saturation (and pH-value), CEC, texture and substrate colour, properties which can roughly be correlated to the different habitats. Nevertheless, a clear distinction between the habitats is not possible because often the influence of termites on the soil properties overrides the effects of the soil genesis and original substrate properties. Transport of subsoil material in combination with changes in the geochemical properties (see excursus termites below) creates a small scale variety within a relatively homogenous substrate. To summarise, the distribution of the profiles can be simplified by the following scheme: Habitat 1 and 2 with Luvisols and Cambisols (eutric), Habitat 3 with Cambisols (dystric) to Arenosols, Habitat 4 with Arenosols to Cambisols, and Habitat 5 with Arenosols. Comparisons with a soil survey on the broader farm area (CLASSEN 2005) revealed a characteristic regional spectrum of soil units in the observatory area except for pan and outcrop situations which are not covered by the observatory.

3.3.3.2 Remarks on classification

The classification of the soil units is given in the WRB (1998) nomenclature. The most important features and the differences of these soils (texture, clay enrichment, colour, partly low CEC, base saturation, pH-value) could be described sufficiently with the qualifiers and reference groups applied. The classification of the Arenosols and Luvisols is explicit due to the texture and clay requirements while the classification of the Cambisols allows some space for interpretation. Considering only the Chromic and Eutric Cambisols the profiles are often identical with the neighbouring Luvisols but miss the required textural difference between top- and subsoil. I assume that these soils are capped Luvisols or were modified by substrate transport due to termite activities. The decision to classify for the Cambisols is the only way to express the properties of these soils correctly but leads to a higher taxonomic variety of the soil association. The application of the new version of the WRB (2006) reveals only minor changes. The new introduced qualifier “clayic” now allows expressing the higher clay contents in some Cambisols and Luvisols.

3.3.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **31**	Ha: **31**	Classification (WRB 1998)	**Dystri-Ferralic Arenosol**
		(WRB 2006)	**Ferralic Arenosol (Dystric)**

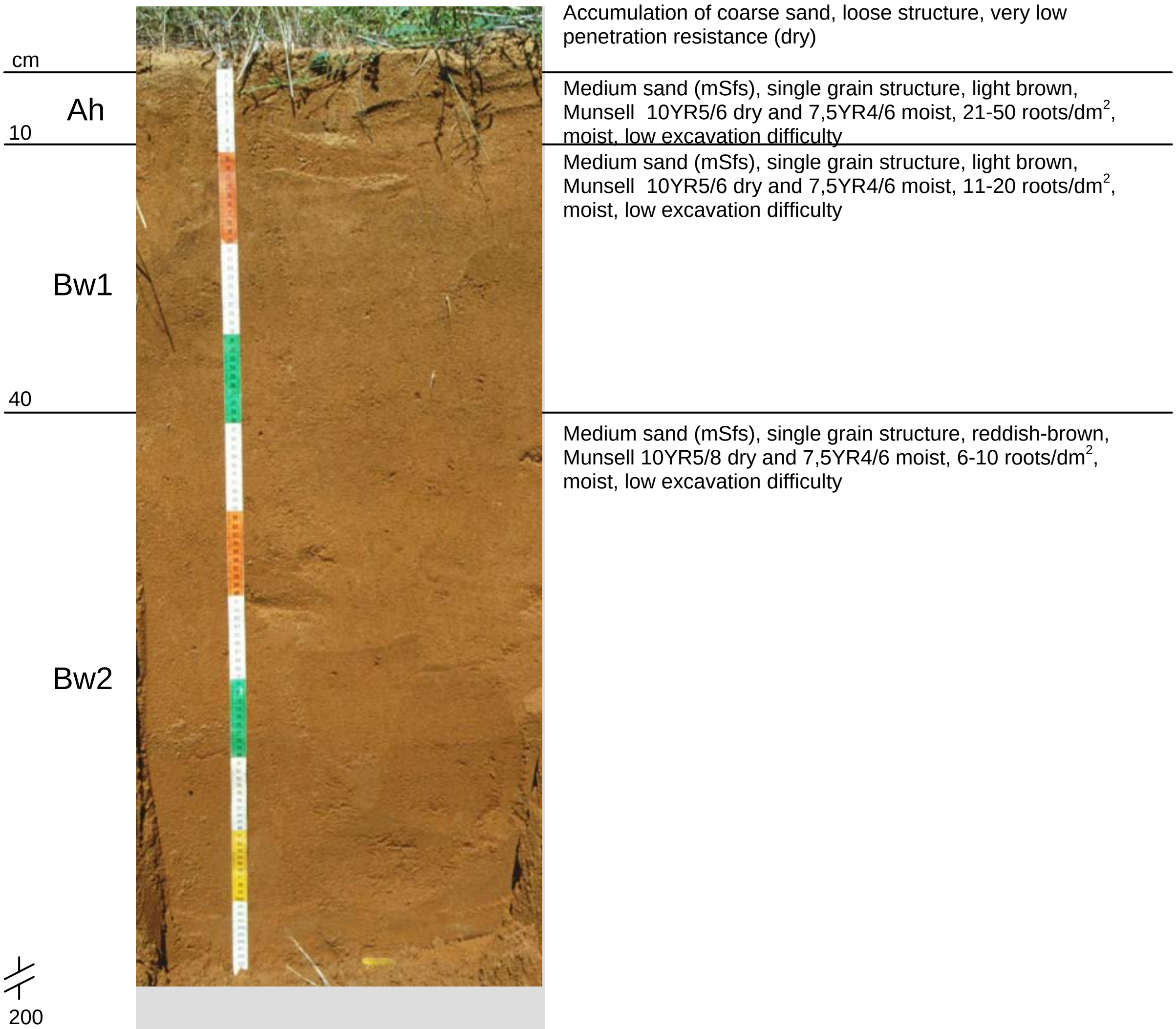


Figure 35 Description of profile 31

The Dystri-Ferralic Arenosol of Figure 35 is a typical example for soils developed in the pure sands characteristic for habitat 5. The mean bulk density is 1.6 g cm^{-1}; the medium sand fraction is dominating and nearly constant across depth. The same is true for the strongly acid pH-values. The organic carbon content and the EC are very low with the highest values in the topsoil and a slight decrease with depth.

In comparison to other Arenosols of previously described observatories where dune sands have low total contents of elements, here the TRB is much higher and comparable with the loamier profiles of habitat 1 to 4. This is mainly caused by high potassium contents indicating sands of different mineralogical composition which are comparatively nutrient rich. Approximately 50 % of the total iron contents are pedogenic oxides indicating a moderate weathering status. The CEC is very low in the topsoil as well as in the deeper horizons, with 20 $mmol_c$ kg^{-1} and around 12 $mmol_c$ kg^{-1}, respectively. The soil is strongly leached, the mean content of water soluble ions is around 3 $mmol_c$ kg^{-1}.

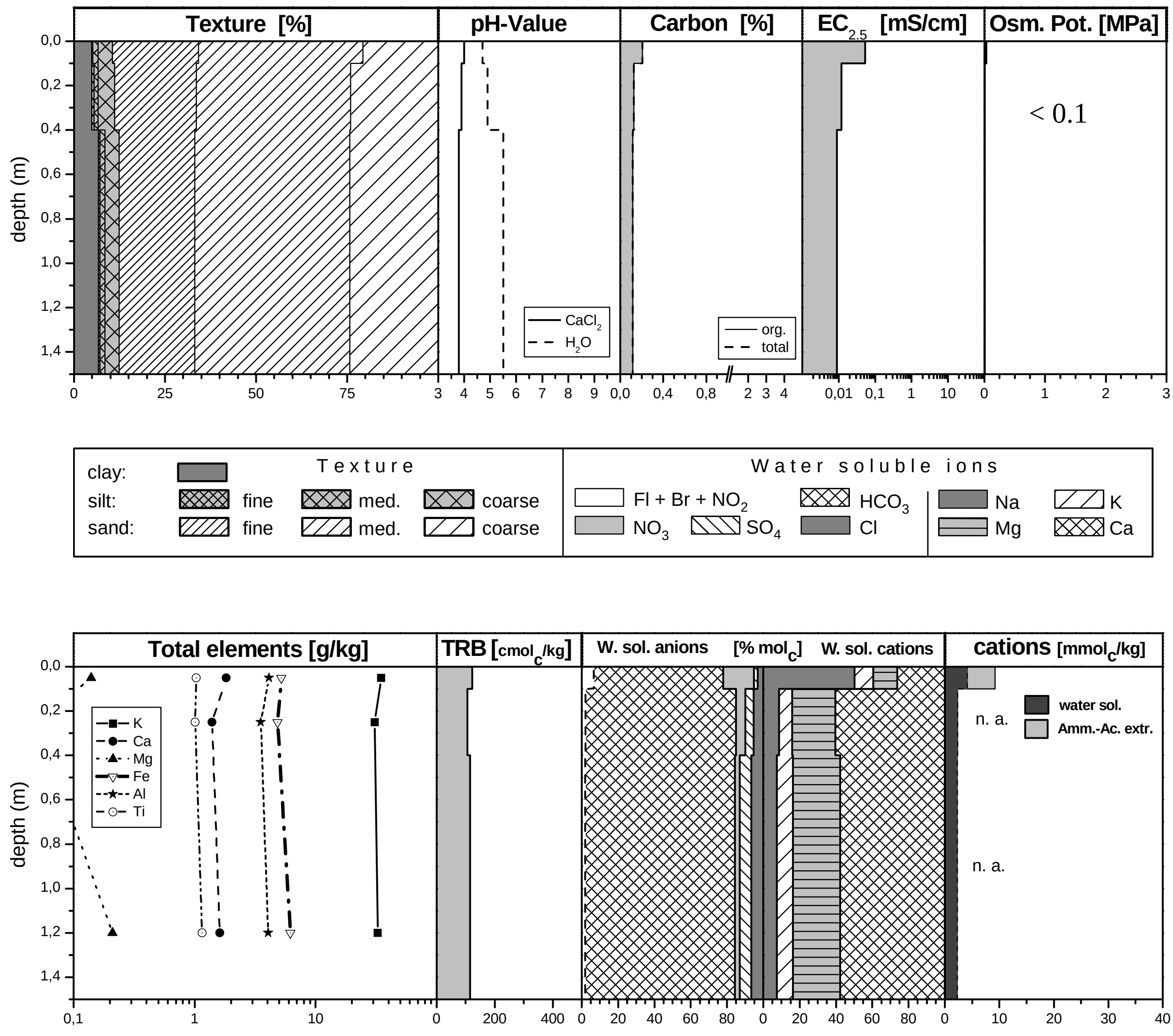


Figure 36 Properties of profile 31

Reference profile # 2

Profile: **39**	Ha: **98**	Classification (WRB 1998)	**Chromic Luvisol**
		(WRB 2006)	**Haplic Luvisol (Endoclayic, Chromic)**

Horizon	Depth (cm)	Description
		Accumulation of coarse sand, patches of microbiotic crust, slight developed vesicular layer, very high penetration resistance (dry)
Ah	0–10	Sandy loam (Sl3) with medium sand (mSfs), subangular blocky structure, brown-dark red, Munsell 7,5YR4/6 dry and 5YR4/3 moist, 21-50 roots/dm², moist, low excavation difficulty
Bw(t)	10–40	Sandy loam (St3) with coarse sand (gSfs), subangular blocky to prismatic structure, brown-dark red, Munsell 7,5YR4/6 dry and 5YR4/4 moist, 21-50 roots/dm², moist, moderate excavation difficulty
Bwt1	40–140	Sandy loam (St3) with coarse sand (gSfs), subangular blocky structure, reddish-brown, Munsell 5YR4/6 dry and 5YR3/4 moist, 21-50 roots/dm², moist to slightly moist, high excavation difficulty
Bwt2	140–155	As above, dry

Figure 37 Description of profile 39

The Chromic Luvisol of profile 39 (Figure 37) is the reference soil of habitat 1 and 2 with reddish, loamy substrates. The texture is differentiated into loamy sand (Sl3) in the topsoil and clay enriched subsoil with clayey sands to sandy clays (St3-Ts4). The sand fraction shows relatively even contents of fine, medium and coarse sand across the entire profile. Bulk density is high with 1.65 – 1.75 g/cm^3 and under dry conditions these soils have a massive, concrete-like character. The pH-values are strongly acid in the topsoil and slightly acid to neutral in the subsoil. The organic carbon reaches ~ 0.35 % in the topsoil and shows only a slight decrease with depth. The electrical conductivity (EC) is very low with a highest value of 50 µS cm^{-1} in the topsoil. For many elements the total concentrations correlate with the clay distribution, aberrant are calcium and potassium which are constant over the profile depth. The TRB is only slightly higher than in the Arenosols of habitat 5. Despite their intensive reddish colour the Luvisols and Cambisols have a relatively low content of pedogenic iron oxides of 40-50 % which indicates a moderate weathering status. The CEC correlates with the clay fraction with values of 30-70 mmol$_c$ kg^{-1}, but the content of water soluble ions is very low with 2-5 mmol$_c$ kg^{-1}.

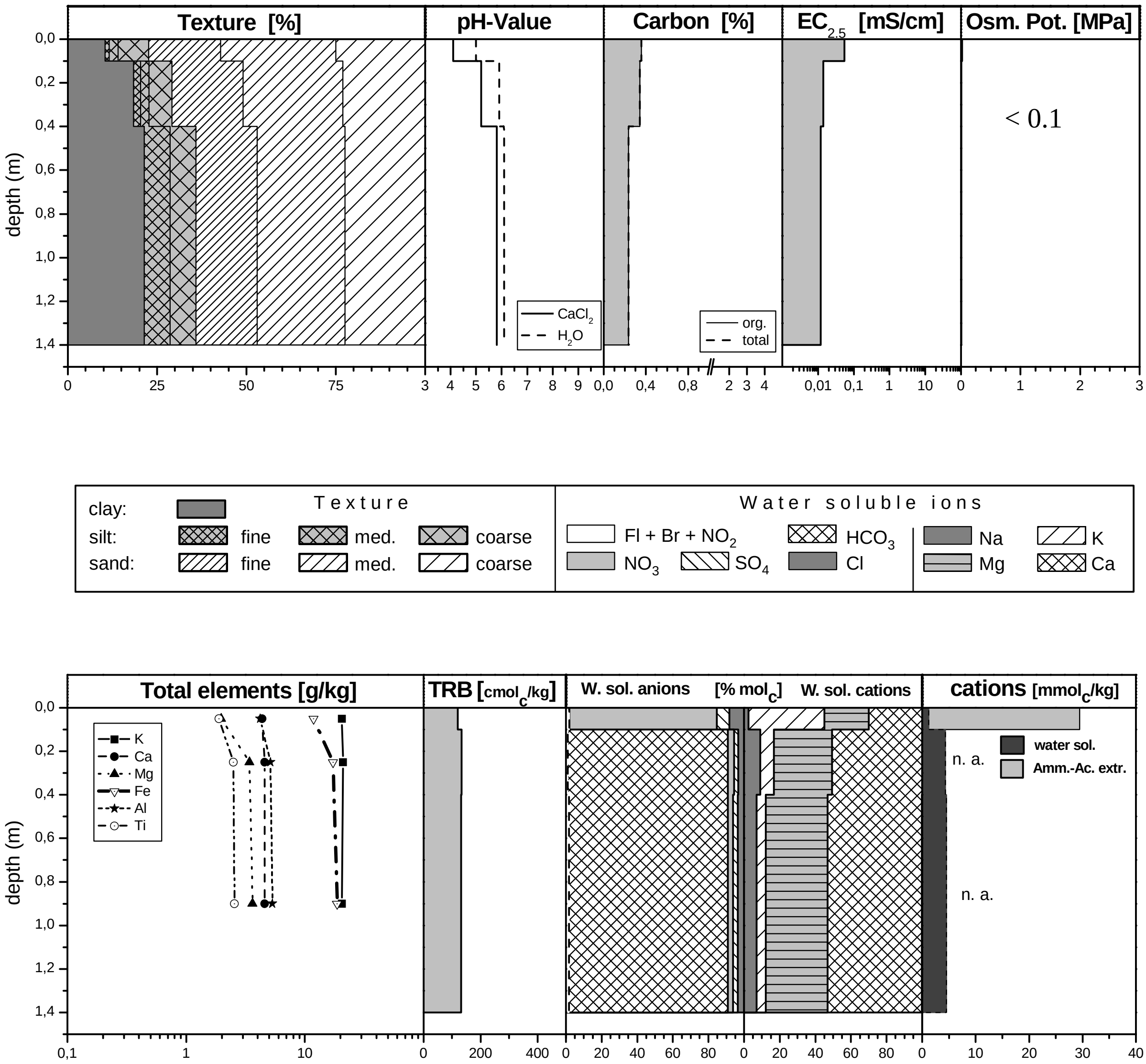


Figure 38 Properties of profile 39

Reference profile # 3

Profile: **35**	Ha: **45**	Classification (WRB 1998)	**Dystric Cambisol**
		(WRB 2006)	**Haplic Cambisol (Dystric)**

Figure 39 Description of profile 35

Within habitat 3, Dystric Cambisols are the typical soil unit. The soils have developed in yellowish brown loamy sand to sandy loam substrates. In comparison to the Chromic Luvisols, the texture shows only a slight clay increase with the depth and in the sand fraction the coarse sand fraction is smaller. The bulk density is comparably high (1.6 – 1.7 g cm^{-3}), and under dry conditions the subsoils have a comparatively massive, concrete-like character.

The pH-values are strongly acid in the topsoil and slightly acid in the subsoil. The organic carbon and the electrical conductivity (EC) are very low. The total element concentrations and the TRB are correlating to the distribution of clay and show parallels to the Chromic Luvisols (reference profile #2). Similar to the previous profiles the content of pedogenic iron oxides is relatively low (40 -50 %), indicating a moderate weathering status. The CEC correlates to the clay content with values of 22 – 35 $mmol_c$ kg^{-1} and the content of water soluble ions is very low.

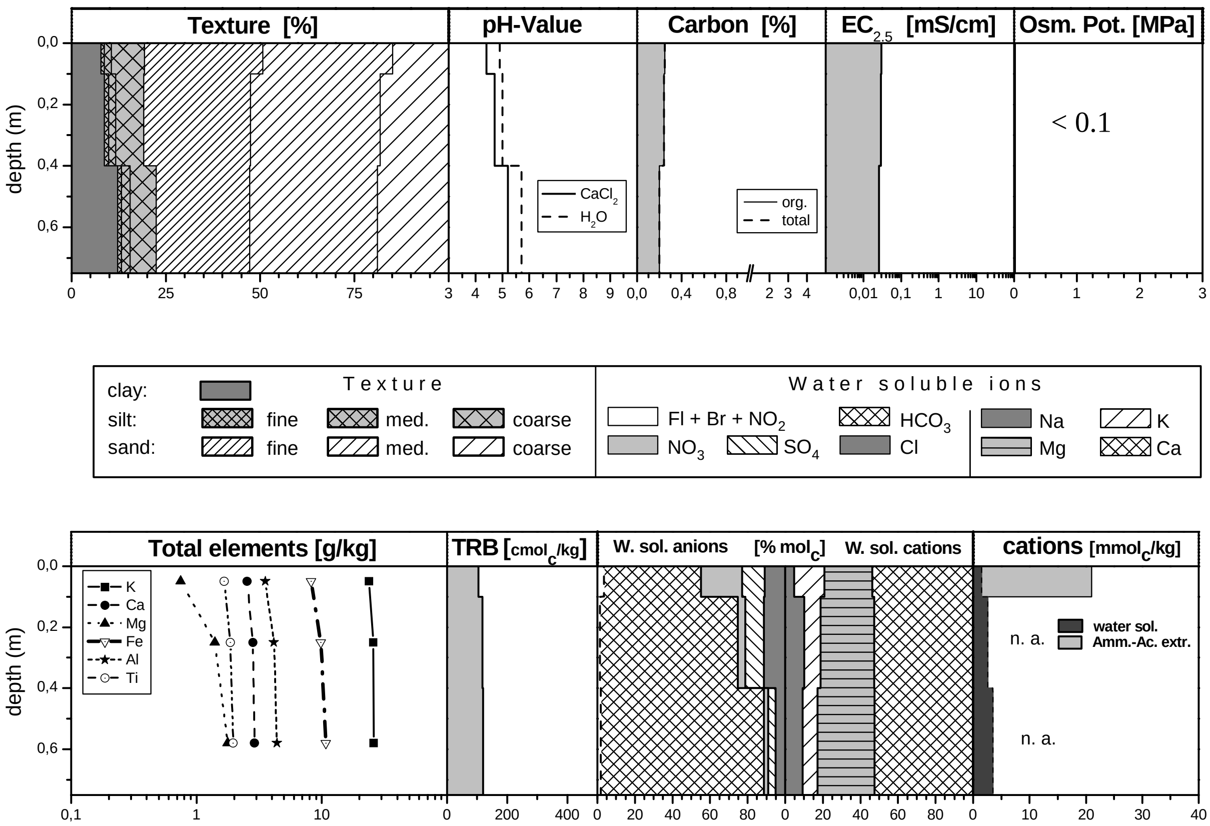


Figure 40 Properties of profile 35

Reference profile # 4

Profile: **50**	Ha: **15**	Classification (WRB 1998) **Dystri-Ferralic Arenosol** (WRB 2006) **Ferralic Arenosol (Dystric)**

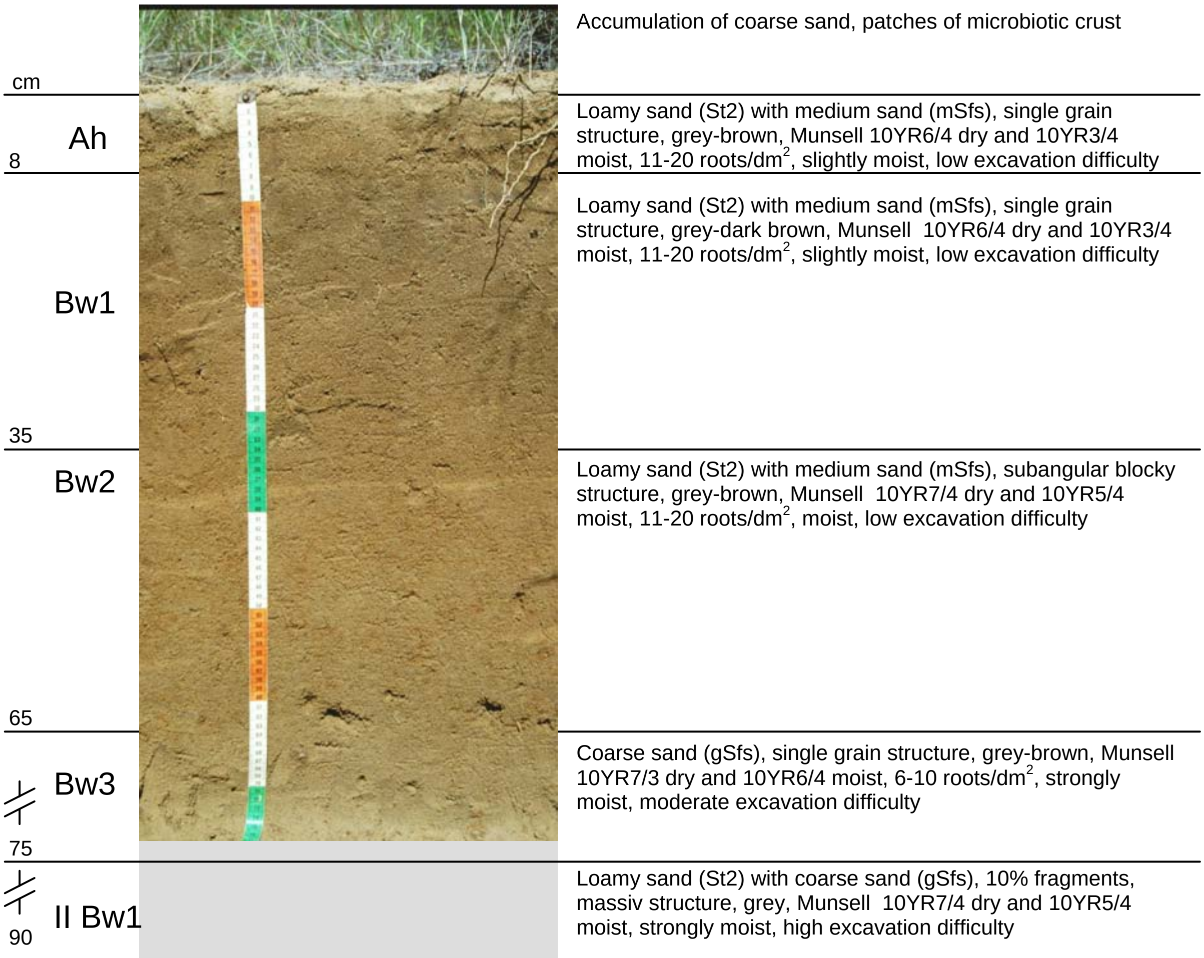


Figure 41 Description of profile 50

A Dystri-Ferralic Arenosol has already been described as reference profile (#1) for habitat 5. Profile 50 (Figure 41) belongs to the same soil unit but shows different properties as a reference for habitat 4. Here, an association of Arenosols and the previously described Dystric Cambisols has developed in pale, sandy to loamy substrates which often show signs of stratification in approx. 1 m depth. A sandy substrate free of coarse fragments overlies a pale to grey, much denser and loamier substrate, in the border zone often accompanied with rock fragments that show signs of fluvial transport. Another prominent feature of this transition zone is the (in situ) accumulation of iron and manganese oxides in form of concretions. The Dystri-Ferralic Arenosol described above consists of loamy sand to sand with a bulk density of 1.6 g cm^{-3} but a relatively loose structure compared to previous profiles. The pH-values are strongly acid in the topsoil and increase sharply to neutral in the lowest horizon. Both, the organic carbon and the electrical conductivity (EC) are very low. The total element concentrations and the TRB show now significant changes with depth except for lower values of iron and magnesium in the sandy horizon in 70 cm depth. The CEC reaches values between 17 and 20 mmol$_c$ kg^{-1}. The mottles of iron oxides occurring below the depth of 35 cm indicate hydromorphic processes which are likely to occur in many profiles of the observatory with loamier subsoils but are often are undetectable due to the reddish substrate colours. In this profile the lower hydraulic conductivity of the fifth horizon reduces the deep drainage which leads to water logging for short time spans. The increase of the EC in the deepest horizon can also be interpreted as an effect of this reduced percolation. The content of pedogenic iron oxides compared to total Fe is 40-50 % except for the lowest horizon where it is only 28 %. This is considered a sign of substrate change, in particular as the horizon above is sandy which strength the theory of stratified substrates.

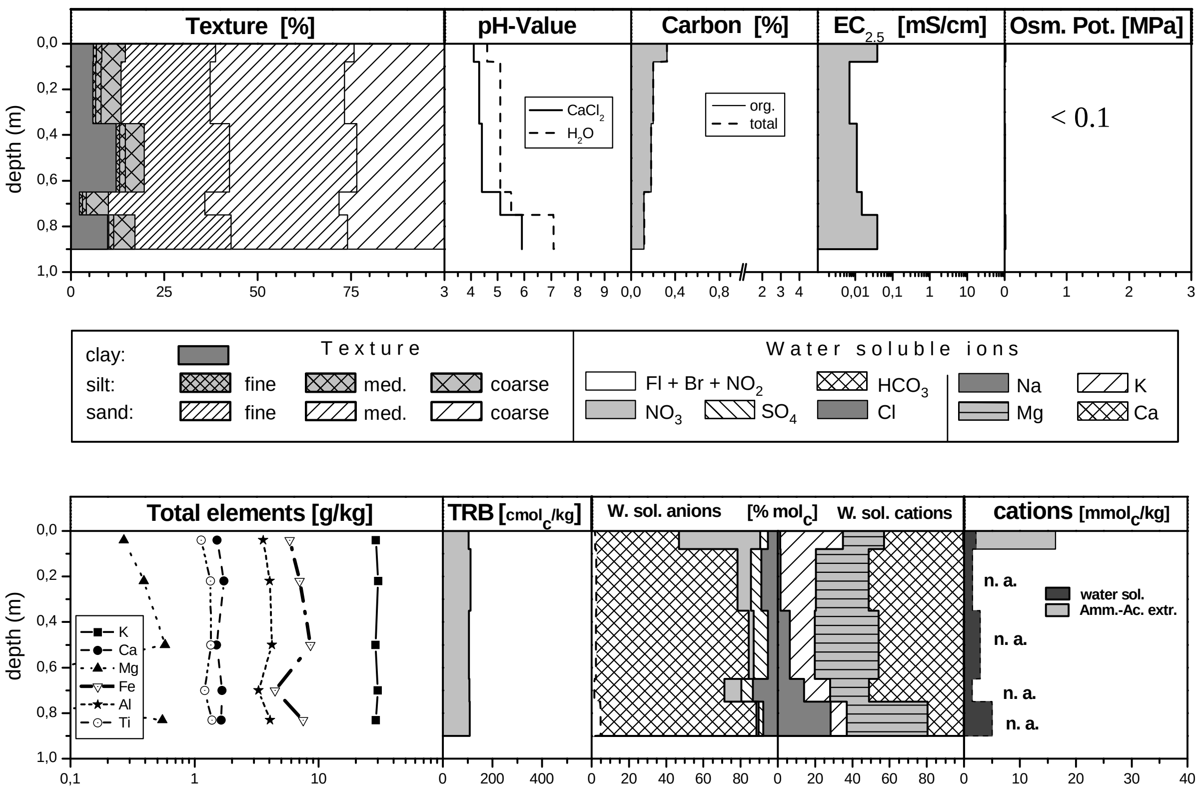


Figure 42 Properties of profile 50

3.3.3.4 Discussion of soil properties

Figure 43 depicts the variability of selected soil properties in three different depths intervals based on data of 40 profiles each. The pH-values show a relatively high range with an increase towards the deeper horizons. The EC is very low with little variation and with slightly higher values in the topsoil. These low contents of soluble salts, comparable with the nutrient status of rainwater, indicate a deep drainage of the soils. Within the topsoil layer, the total range of organic carbon is large whereas the majority of OC values have only small ranges in each dataset and show a slight decrease in median values with depth. In contrast, the fine particle percentage (clay & silt) increases with depth and varies a lot. Except for a few profiles in contact with the underlying bedrock the rooting space (RS) is near 100 % in all investigated profiles. The variability of soil properties is not only a result of differences between habitats and soil units, but is additionally the effect of termite activities that leads to small scale changes in the parameters pH, EC and texture within all habitats.

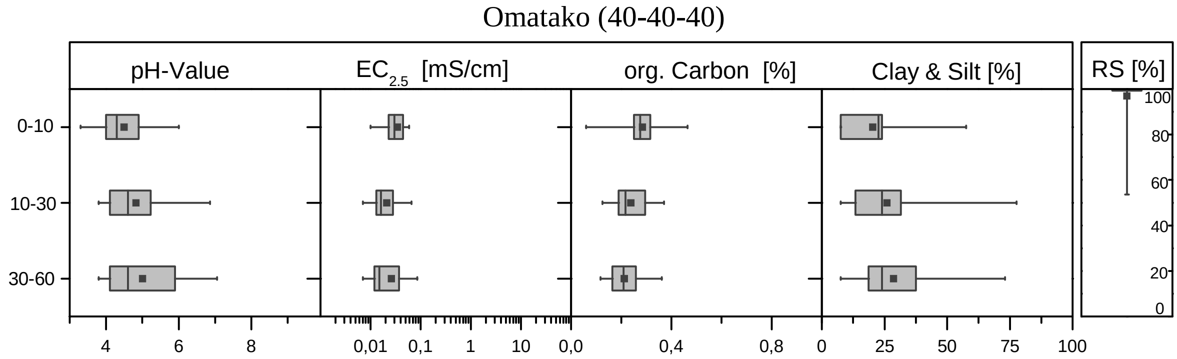


Figure 43 Variability of selected soil properties in three depth intervals for the observatory #04

Box =25-75% with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top→ down), RS= rooting space

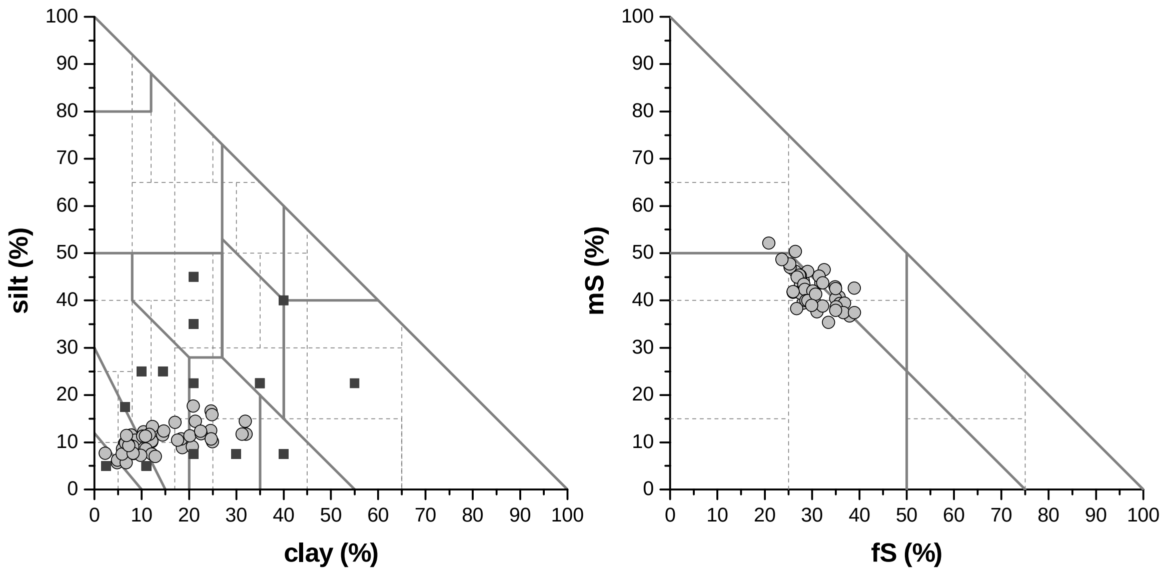


Figure 44 Results of the texture analyses for the observatory #04 Omatako

squares = finger test (all samples)and circles = lab analyses (selected samples)

Figure 44 shows the results of the texture analyses of all samples for the observatory #04. Texture ranges from sand to sandy clay and only few samples have higher silt contents. This clay/sand mixture is a unique feature of these savanna soils. With regard to the sand fractions, the samples have a fairly constant amount of coarse sand (~ 20 %) and typically slightly more medium than fine sand contents (mSfs, gSfs). High coarse sand proportions indicate that the substrates are not strongly influenced by wind blown sands. This influence becomes more important towards the eastern direction of the region (Kalahari sands). More likely, the differences in substrates within the observatory are a result of the heterogeneity of underlying bedrock material, i.e. the lithology of the area. During the survey three different kinds of rock were found in the profiles or on the surface as a result of burrowing animals, i) pegmatic granites with large minerals, ii) 'standard' granites and iii) fine structured sandstones like granite. I assume that these bedrocks have influenced the substrate genesis by different weathering behaviour. Moreover, the massive transport of soil parent material during the landscape evolution might also have been an important factor for substrate differentiation. The stratification within habitat 4 is a result of these processes.

The striking pattern in vegetation distribution with high tree and bush densities in habitat 1 and 2, more open, grassy character of habitat 3 and only a few trees in habitat 4 correlates with the distribution of soil texture and CEC (as a result of clay content). Most probably, nutrients are not the dominant factor responsible for this vegetation structure as the EC status across all habitats is equally low. It is more likely that the driving ecological effect of the sequence of pure sands in habitat 5 to sandy clay loam in habitat 1 is caused by the variation in water supply. Why different dominance patterns of growth forms (grass, bush and tree) emerged remains an open question.

The dominant stands of *Sida cordifolia* in habitat 5 are the result of permanent disturbances by burrowing animals and trampling of the Elands using this site as their preferred stand.

EXCURSUS: Termites

Wide parts of the central Namibian Savanna are influenced by the activity of the mound building and fungus growing termite *Macrotermes michaelseni* (Sjöstedt). On the observatories #04, Omatako and #05, Otjiamongombe these termites have major influence on the micro-habitat structure and soil properties. Therefore this excursus shall briefly describe the ecological importance of termites in the area.

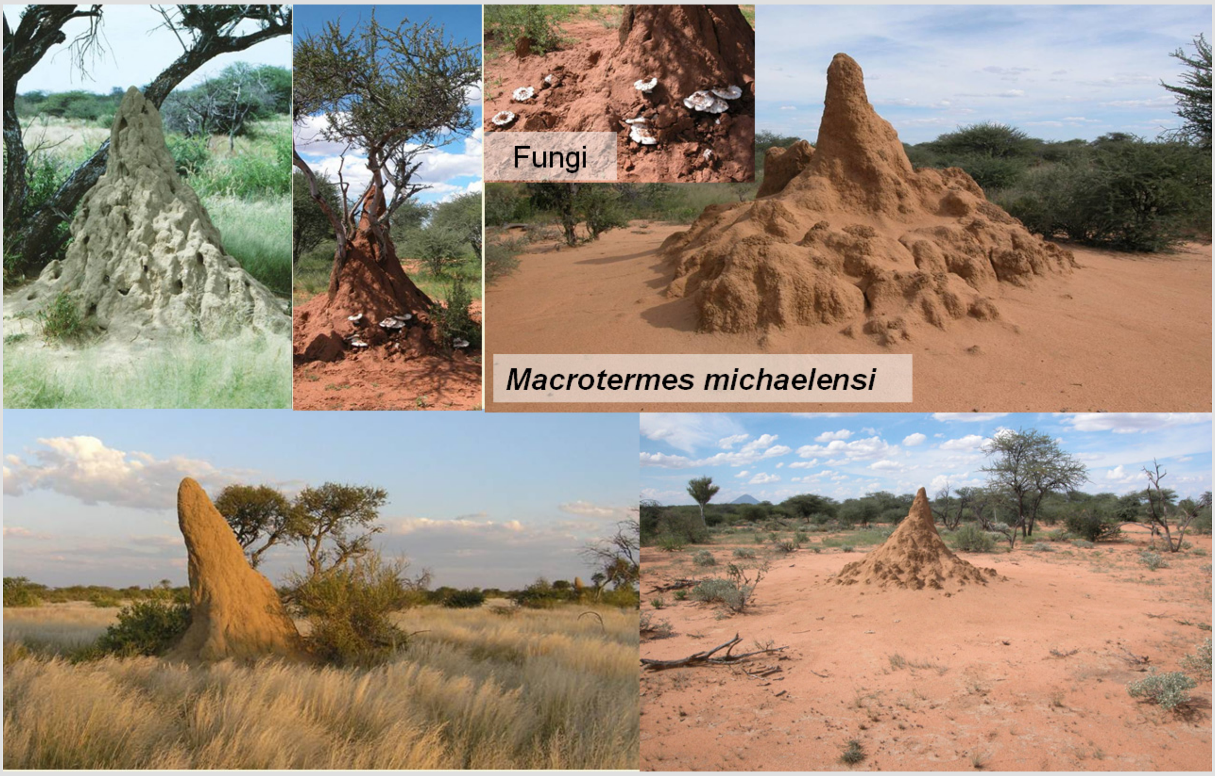


Figure 45 Termite mounds of *Macrotermes michaelseni*

Mound building termites in arid and semiarid regions are often regarded keystone species, because they are structuring their habitats through soil turnover and decomposing plant material (HOLT & LEPAGE 2000, TURNER 2000, 2001, JOUQUET et al. 2005, 2006). Regarding the basic scheme in Figure 46 it is obvious that this has to lead to an actual patchy structure in soil properties or in the long run to a permanent mixing process which could again lead to homogeneity.

Data concerning this matter are very rare for the southern African savannas and also the detailed soil survey of the observatories reveals more questions than answers regarding the processes. One focus in an ongoing BIOTA study is therefore the analysis of the process of

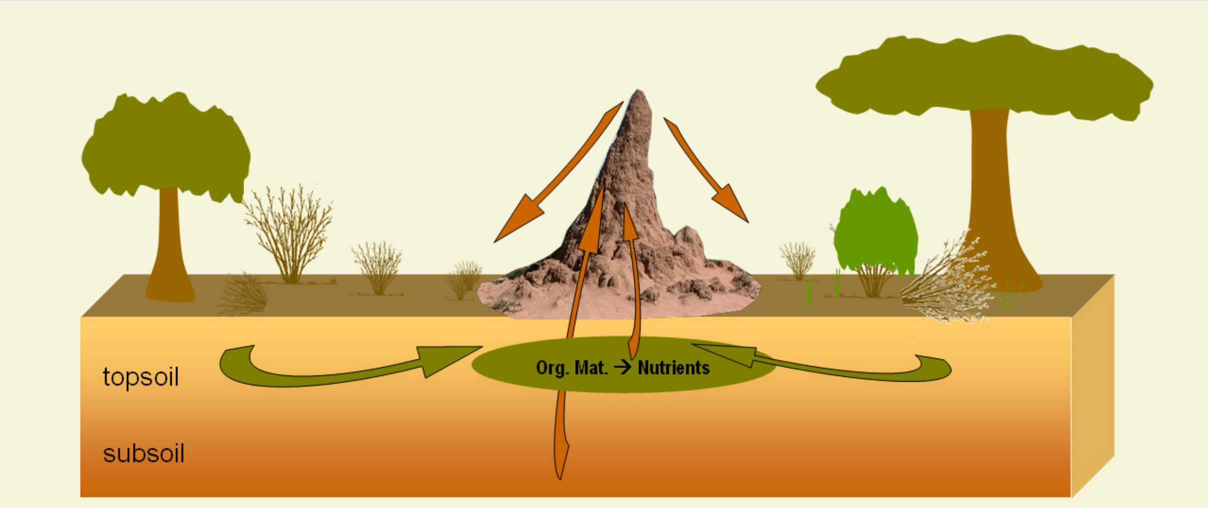


Figure 46 Scheme of soil and nutrient transport by mound building termites

soil and nutrient cycling by the building and decay of the mound and the redistribution of soil material and nutrients (GROHMANN, unpublished data). Investigations of SCHWIEDE et al. (2005) in Kalahari soils also showed enrichment of nitrate in spatial context with termite mounds.

The results of the soil survey for the observatories revealed a variety of active, decaying and decayed mounds which all show a typical circle of 5 – 20 m in diameter with distinct soil properties relative to the surrounding matrix soils. The most dominant feature is the texture which always shows higher clay contents and is obviously subsoil material. Often these flattened circles or remnants of the mounds also show higher nutrient contents (soluble salts) which might be an important feature in the nutrient poor area. A striking feature is also the physical crusting of these circles which in combination with slight inclination obviously increases the run-off rates from these micro habitats which are often bare. Only in micro depressions plant growth re-colonises these patches underlining the soil physical restrictions as the main cause for the bare status and slow re-vegetation.

Although it is assumed that the termites are the major decomposers of woody plant material, relatively low contents of organic carbon are found in the mounds or mound–remnant sites. This indicates a highly effective decomposition of plant material. The increased nutrient contents of the mound material could therefore be the mineralised remainder of the organic matter. Moreover, the ion composition revealed a dominance of nitrate. However, as the termites prefer subsoil material for their constructions it cannot be excluded that they use material from deeper substrate layers which could be enriched in nutrients resulting from drainage processes.

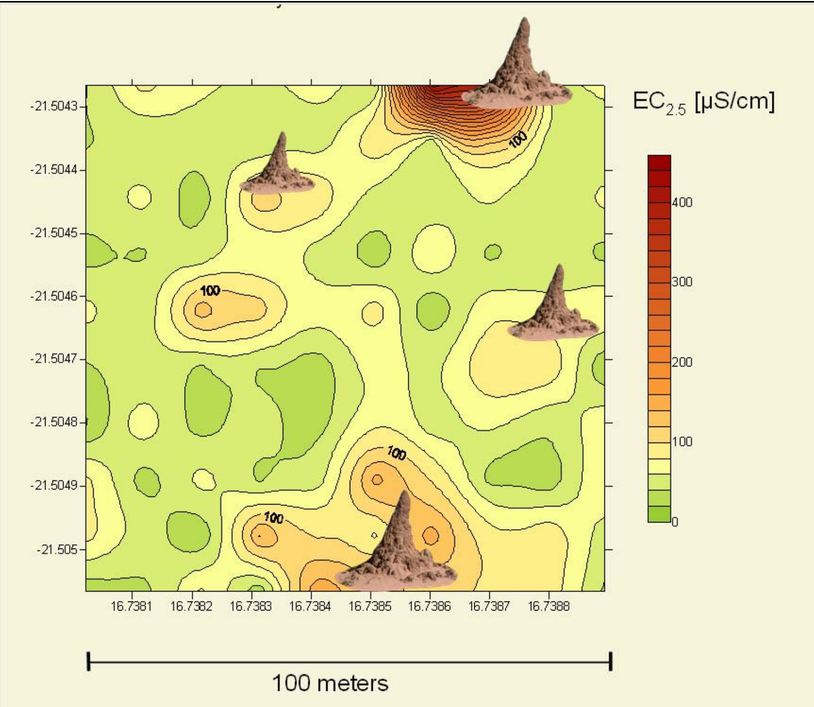


Figure 47 Spatial pattern of EC and location of termites mounds on the ha 39 (observatory #04)

Figure 47 shows the result of a fine scaled topsoil analysis with a 10 m grid on a one hectare plot on the observatory #04, Omatako. Within this hectare a high range in EC occur and clearly correlates with the position of termite mounds or mound remnants. Together with the differences in texture it shall be pointed out that these micro-habitats of termite mounds strongly influence the small scale patchiness of soil properties and have to be taken into account when interpreting the results of soil surveys.

3.4 Observatory 05 (Erichsfelde / Otjiamongombe)

3.4.1 Regional overview

The observatory #05 Otjiamongombe (commonly called Erichsfelde) is located approx. 45 km north of Okahandja in the Otjozontjupa region on the ‘Erichsfelde’ farm. The farm covers an area of approx. 13,000 ha.

The environmental situation is similar to the previously described observatory #04 Omatako which is located in a distance of 24 km northwest. Mean annual temperature is 20 °C. Potential evaporation rates are 1800-2000 mm a^{-1}. The potential natural vegetation is an open thornbush savanna with *Acacia* species as main woody components and grasses like *Stipagrostis uniplumis, Aristida* and *Eragrostis* species in the herb layer. In some spots there is bush encroachment by *Acacia mellifera*.

Geologically, the region is situated in a transition zone between the western Kalahari borders towards the east and the escarpment in the Damara belt with the Damara supergroup (schists, dolomites) and Damara granite intrusions in the west. The drainage system is pointing northwards, towards the borders of the Omatako catchment.

The topography of the farm area is almost flat to gently undulated with a mean height of 1510 m asl. Major landforms are plains and for smaller parts riviers, pans and some rocky outcrops. An important feature is the Ombutozu inselberg in the west of the farm with a height of 1916 m asl (SCHNEIDER 2004). Extensive cattle and game farming are the dominant forms of land-use in the area and on the farm (BUSS 2006). The most important pressure on the environment is overgrazing which leads to a shift in natural vegetation (e.g. bush encroachment).

3.4.2 Observatory description

The observatory itself is located in the north eastern part of the farm. The topography is flat with a mean height of 1512 m asl and a slight inclination towards the north. The western part is dissected by a small rivier in south/north direction. The unconsolidated substrates consist of loamy textures with different colours varying from greyish brown in the western part to reddish in the mid and eastern parts of the observatory. Below the substrates is to some extent a calcrete layer. Vegetation structure varies only little except for larger trees along the rivier. Main species are *Acacia mellifera*, *Acacia erioloba, Catophractes alexandri, Monechma genustifolium, Stipagrostis uniplumis* and *Aristida congesta*. Habitat differentiation was only made for plains and rivier affected sites.

3.4.3 Soils

3.4.3.1 Main soil units

According to the standardised sampling scheme 25 soil profiles were investigated and sampled. The different soils units of the observatory #05 Otjiamongombe and their distribution are shown in Figure 48.

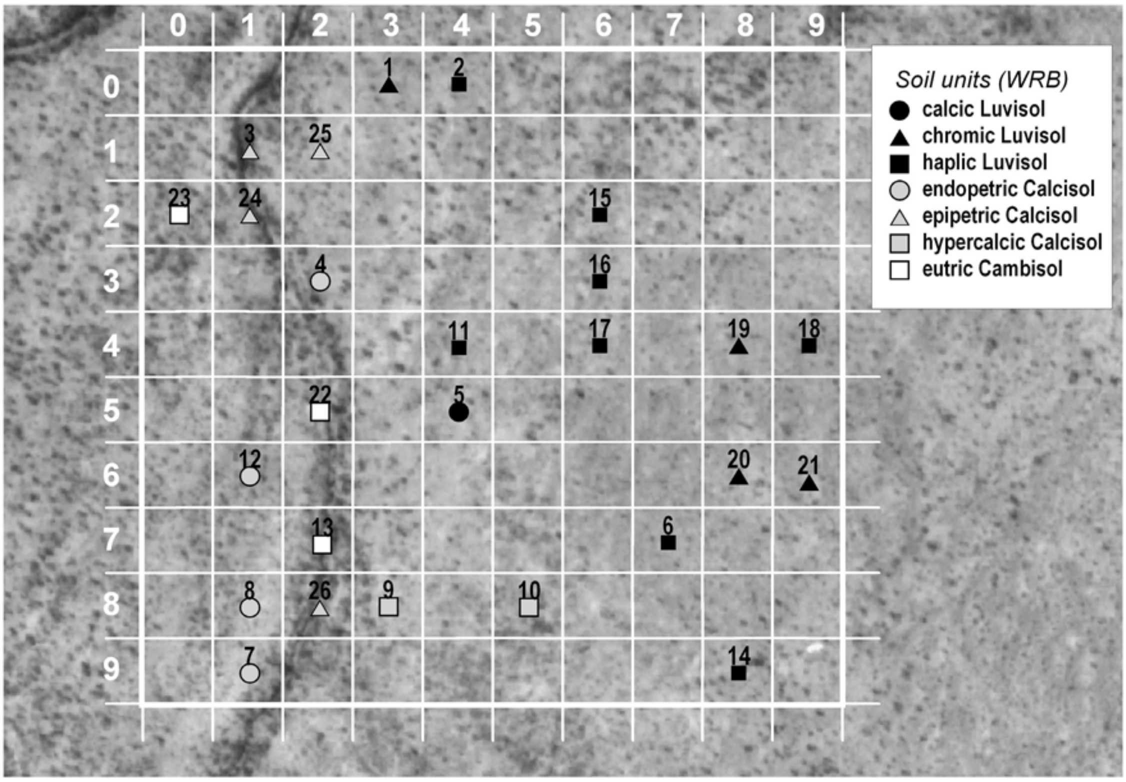


Figure 48 Distribution of soil units (WRB 1998, 1st qualifier level) on the observatory #05 Otjiamongombe

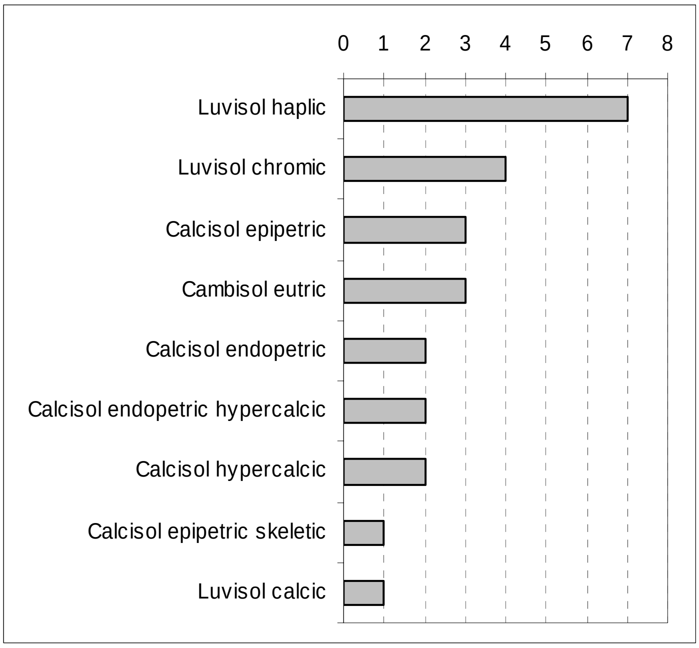


Figure 49 Frequency distribution of WRB (1998) soil units in observatory #05 (Otjiamongombe)

Luvisols and Calcisols are the dominant reference groups, accompanied by a few Cambisols. The distribution of the soil units on the observatory displays a clear pattern: Luvisols occur in the eastern part of the observatory while Calcisols are restricted to the western part along the rivier structure. The Calcisols are defined by a *petro*calcic horizon. The shallowest profiles are situated along the rivier and are often dominated by *Catophractes alexandri*. The substrate consists of dark, partly heavy textured loams typical for the western part of the observatory. Also the accompanying Cambisols have developed in this material but lack the strong accumulation of calcium carbonate. A common feature of all carbonate rich soils is the strongly developed biological soil crust (BSC). In the carbonate-free substrates in the eastern part of the observatory these crusts are only weakly developed or missing. The Luvisol association is developed in the deep loamy, reddish substrates. Depending on the colour the qualifier chromic is used, in one case a Calcic Luvisol was found in the transition from Calcisols to Luvisols. A common feature of all soil units is the cover of a thin layer of coarse sand that can be regarded as a residual of erosive processes. Additionally, a vesicular layer in the first centimetres occurs frequently.

An additional study focuses on the possibilities of remote sensing technique for soil spatial analyses in the study region and gives information about additional soil situations on the farm level (for details see CLASSEN (2005), GRÖNGRÖFT et al. (2005)).

3.4.3.2 Remarks on classification

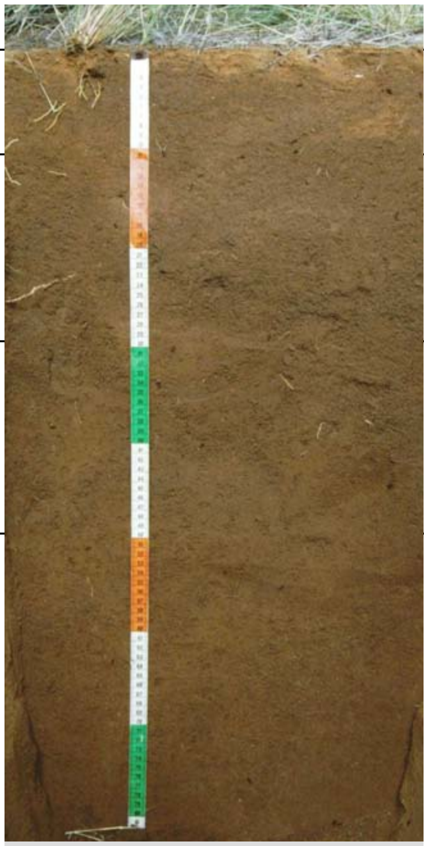
The classification of the soil units is given in the WRB (1998) nomenclature. The most important features and the differences of the soils (clay rich subsoils, calcic horizons, strong red colour, differing CEC and pH-values) could be described sufficiently with the provided qualifiers and reference units. The classification of the Luvisols and Calcisols is explicit due to the texture and calcrete requirements whereas the classification of the Cambisols allows some room for interpretation. The Cambisol profiles show no clear features for in situ structural development, the homogenous dark colour could also be the result of a colluvial development. Several soil profiles in the western part of the observatory (west of the rivier) are assumed to be influenced by allochton or colluvial material which is more recent than the more reddish loamy substrates in the eastern part of the observatory. However, there are no clear signs of stratification which would be a prerequisite to assign it with 'fluvic' properties. Thus, depending on the interpretation of the properties, different classifications of these soils are possible. Assuming that the material has been fluvial deposited would lead to a classification as a Fluvisol. On the other hand, the dark colour and the relatively high content of organic carbon make some topsoils appear to fit to the definition of the 'mollic' horizon which would consequently lead to a Chernozem, Kastanozem or Phaeozem. Indications pointing to the development of such soils in this region are given by EITEL & EBERLE (2001, 2002). However, untypical for these reference groups is the mostly hardsetting structure of the topsoil and neither are other requirements completely met. Therefore the latter classification was dropped. The classification as Fluvisols was also cancelled, as the stratification of the substrate is only detectable by organic carbon and single calcareous nodules that might be of fluvial origin. Although several properties indicate a kind of fluvial origin (this might have been a single event of mudstreams after a heavy thunderstorm rainfall event, fluvial deposits can therefore show a completely different character in comparison to locations with other climatic conditions) the classification as Fluvisols cannot provide a more precise description than the Cambisols.

The application of the new version of the WRB (2006) reveals only minor changes. The newly introduced qualifier 'clayic' now allows expressing the high clay component in the subsoil of some Luvisols and Cambisols.

3.4.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **15**	Ha: **26**	Classification (WRB 1998)	**Haplic Luvisol**
		(WRB 2006)	**Haplic Luvisol (Endoclayic)**



Depth (cm)	Horizon	Description
		Accumulation of coarse sand, patches of BSC, slight developed vesicular layer, very high penetration resistance (dry)
8	Ah	Loamy sand (St2) with coarse sand (gSfs), subangular blocky structure, reddish-brown, Munsell 10YR5/6 dry and 7,5YR3/4 moist, 11-20 roots/dm², slighly moist, moderate excavation difficulty
32	Bw1	Sandy loam (Sl4) with coarse sand (gSfs), subangular blocky structure, reddish-brown, Munsell 10YR5/6 dry and 7,5YR3/4 moist, 6-10 roots/dm², slighly moist, moderate excavation difficulty
50	Bw2	Sandy loam (St2) with coarse sand (gSfs), subangular blocky structure, reddish-brown, Munsell 10YR5/8 dry and 7,5YR3/4 moist, 6-10 roots/dm², dry, high excavation difficulty
110	Bwt1	Sandy loam to sandy clay loam (St3) with coarse sand (gSfs), massive structure, red-brown, Munsell 10YR5/8 dry and 7,5YR4/4 moist, 6-10 roots/dm², dry, high excavation difficulty
120	Bwt2	Sandy clay loam (Ts4) with coarse sand (gSfs), massive structure, red-brown, Munsell 10YR5/8 dry and 7,5YR4/6 moist, few mottles (Fe), 6-10 roots/dm², dry, high excavation
145	Bwt3	Sandy clay loam (Ts4) with coarse sand (gSfs), massive structure, inhomogenous colour, Munsell (mixed sample) 10YR5/4 dry and 10YR4/4 moist, many prominent mottles (Fe & Mn), 6-10 roots/dm², dry, high excavation difficulty

Figure 50 Description of profile 15

The Haplic Luvisol described above is a typical example for soils developed in the reddish loamy substrates without calcretes. The texture is dominated by a sand clay mixture with an even distribution of the different sand fractions and only little amounts of silt. Clay content increases with depth up to 30 % and the mean bulk density is around 1.65 g cm^{-3}. Soil reaction is slightly acid across the entire profile; EC is low with a marginal increase with depth. Total element contents and TRB increase with profile depth showing a clear correlation with the clay content. Pedogenic iron is around 40 % of the total iron content indicating a moderate weathering status. The content of water soluble ions is very low with 3-10 mmol$_c$ kg^{-1}. The CEC is between 40 and 110 mmol$_c$ kg^{-1}.

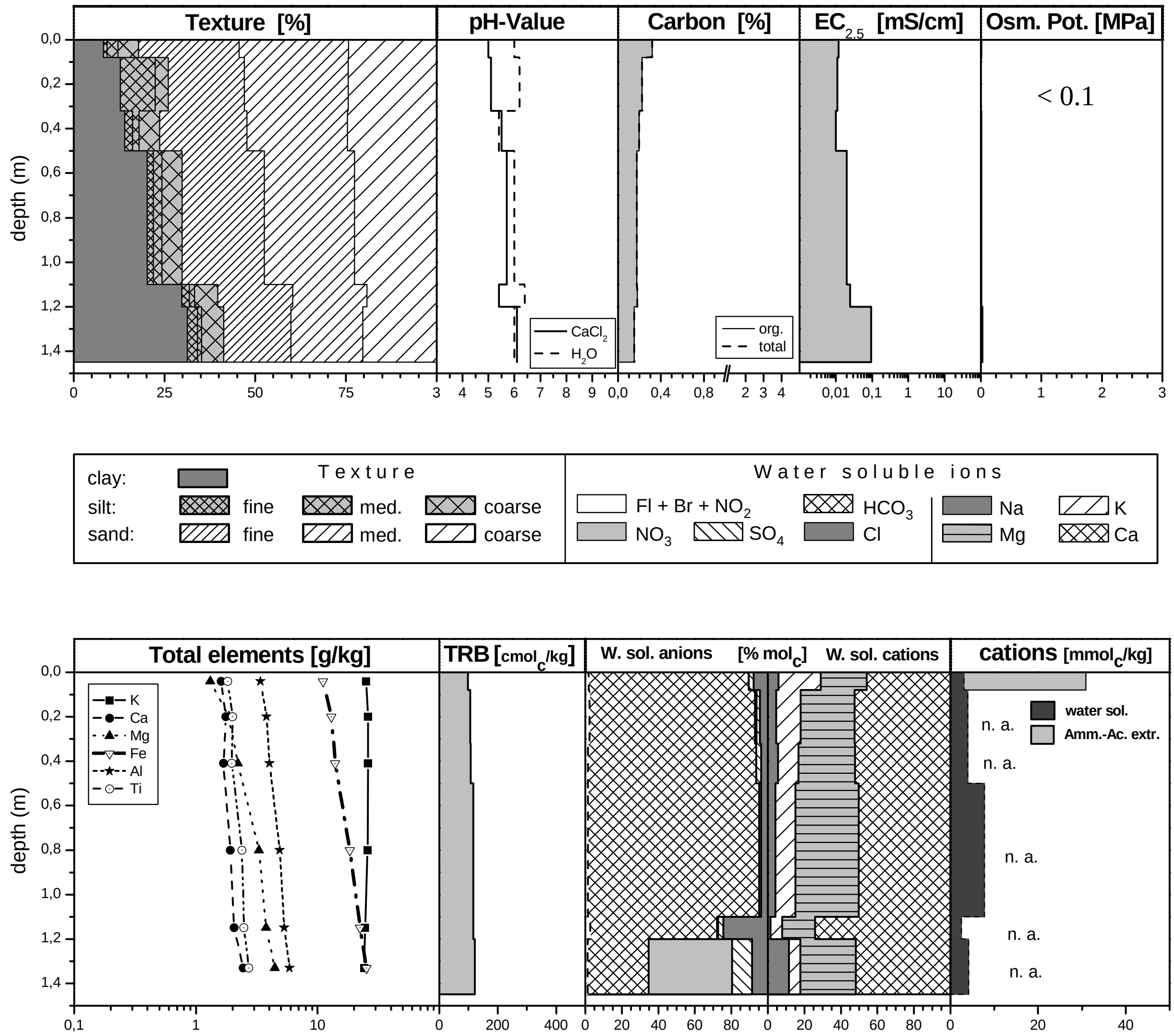


Figure 51 Properties of profile 15

Reference profile # 2

Profile: **25**	Ha: **12**	Classification (WRB 1998)	**Epipetric Calcisol**
		(WRB 2006)	**Epipetric Calcisol**

cm	Horizon	Description
		Accumulation of coarse sand, strong developed BSC, low penetration resistance (moist)
10	Ah	Sandy loam (Sl4) with coarse sand (gSms), subangular blocky structure, reddish-brown, Munsell 7,5YR4/6 dry and 7,5YR4/4 moist, 21-50 roots/dm^2, slighly moist, moderate excavation difficulty
20	Bw	Sandy loam (Sl3) with coarse sand (gSfs), subangular blocky structure, few calcareous nodules, reddish-brown, Munsell 7,5YR4/4 dry and 7,5YR3/4 moist, 21-50 roots/dm^2, slighly moist, moderate excavation difficulty
30	Bwkc	Sandy loam (Sl4) with coarse sand (gSfs), subangular blocky structure, few calcareous nodules, moderately calcareous, reddish-brown, Munsell 7,5YR4/6 dry and 5YR4/3 moist, 21-50 roots/dm^2, dry, moderate excavation difficulty
38	Ckc	Sandy loam (Sl4), subangular blocky structure, 90 % fragments of calcareous nodules, strongly calcareous, 11-20 roots/dm^2, dry, high excavation difficulty
40+	Ckm	Calcrete (massive)

Figure 52 Description of profile 25

The Epipetric Calcisol of Figure 52 is a typical example for the soils developed in the transition zone between Luvisols in the eastern and Calcisols in the western part of the observatory where calcretes or petrocalcic horizons occur within 1 m depth. In this transition zone the reddish substrate colour above the calcic horizon dominates whereas in the western part of the observatory dark soil colours are prominent.

The texture of these reddish Calcisol profiles varies from loamy sand to sandy loam with an even distribution of the different sand fractions. The mean bulk density is around 1.65 g cm^3. The petrocalcic horizon starts with a thin nodular crust which evolves to a massive structure below. Often the fine earth within the nodular crust horizon is free of carbonates. The soil reaction is neutral across the entire profile; EC is low with 100 µS cm^{-1} but significantly higher than in the Luvisols and Cambisols. Total element contents of the fine earth are constant except for the slight increase of calcium and magnesium in the horizon above the nodular crust.

The content of water soluble ions is very low with 3-10 mmol$_c$ kg^{-1}. CEC is not analysed for this profile. The relatively high values for the ammonium acetate extractable cations could be a result of the dilution of calcium carbonates during the extraction process.

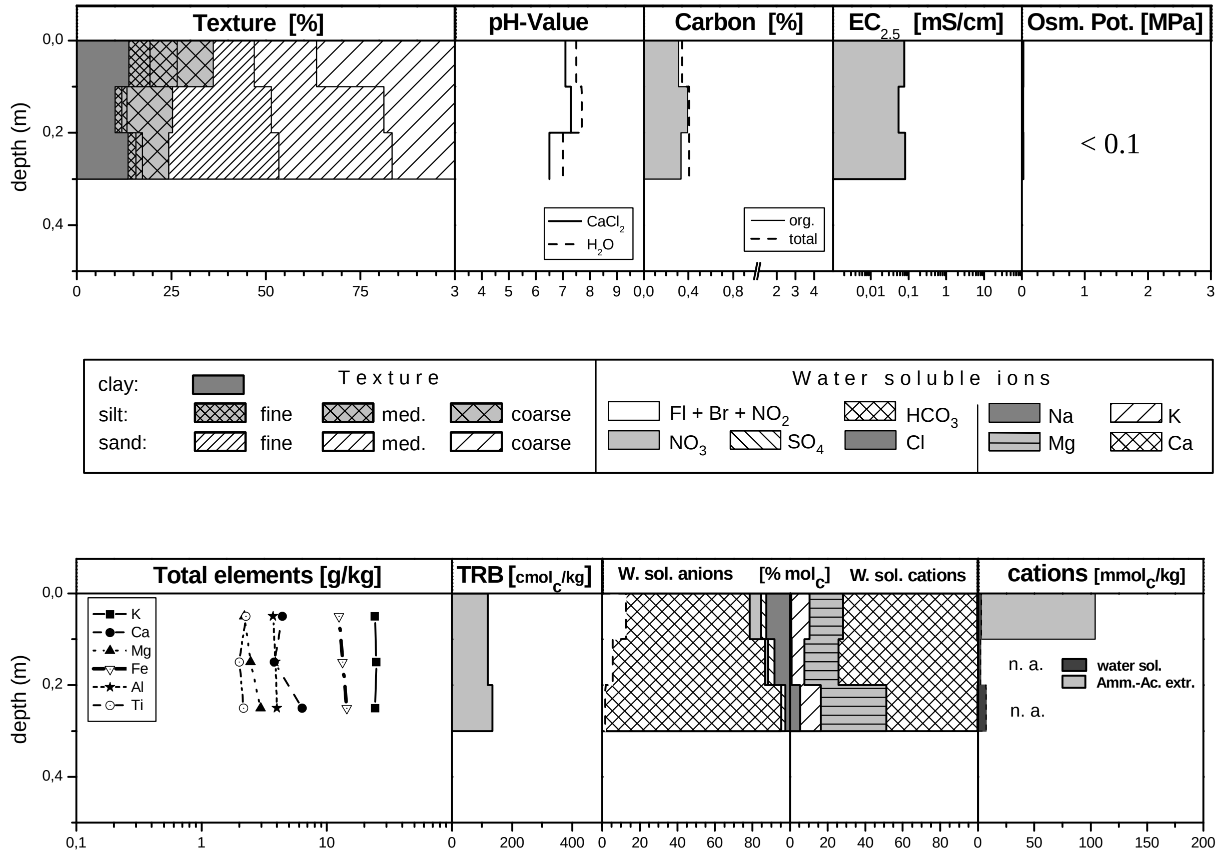


Figure 53 Properties of profile 25

Reference profile # 3

Profile: **8**	Ha: **81**	Classification (WRB 1998) **Hypercalci-Endopetric Calcisol** (WRB 2006) **Hypercalcic Endopetric Calcisol**

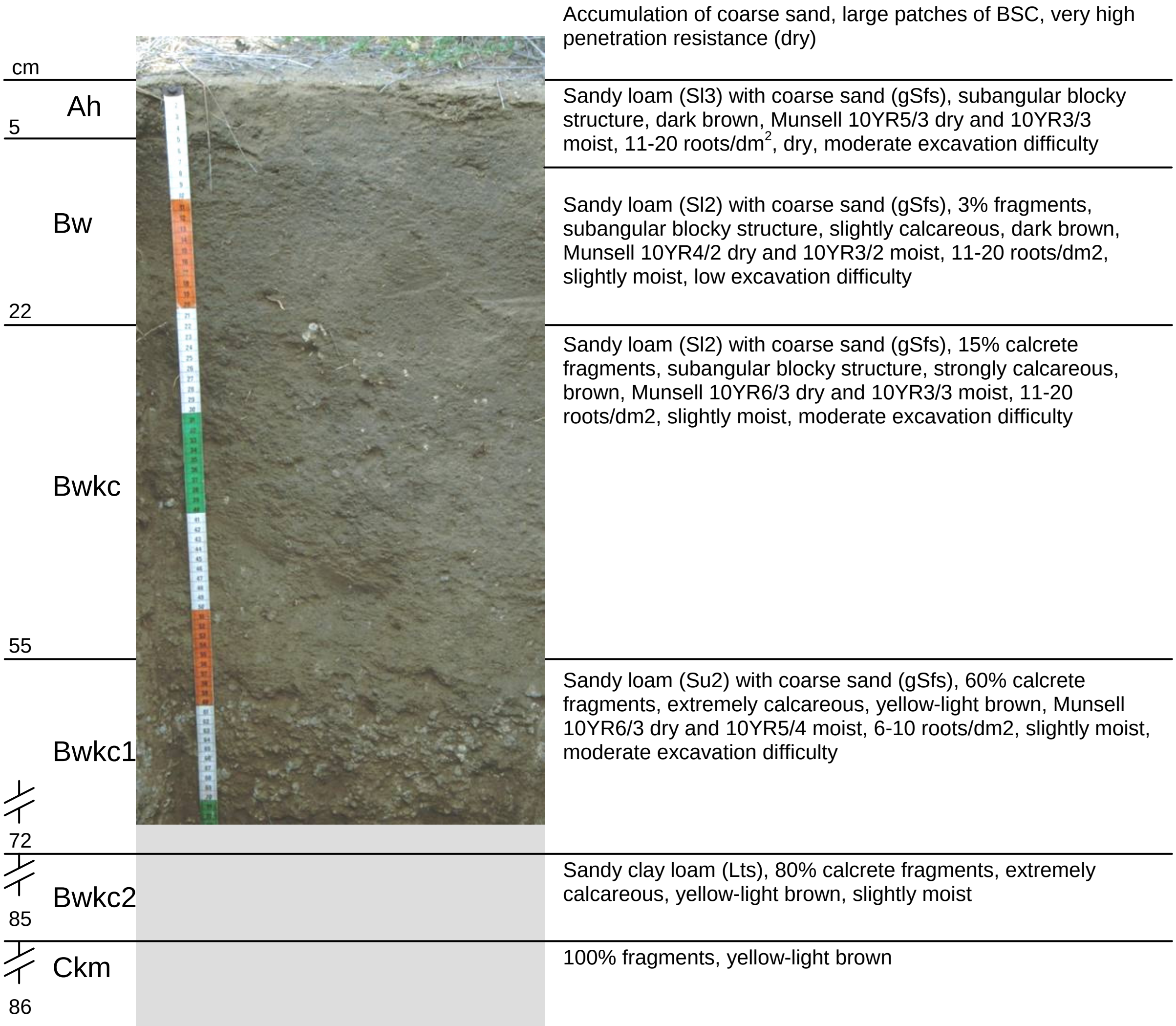


Figure 54 Description of profile 8

The Endopetric Calcisol of Figure 54 is an example for soils developed in the western part of the observatory where calcretes or petrocalcic horizons occur within 1 m depth which are with covered dark brown and loamy topsoil. If the calcic horizons were missing within 1 m depth the soils were classified as Cambisols having quite similar soil properties. A dominant feature is the strongly developed biological soil crust on the surface often found in carbonate rich substrates.

The texture of the soils ranges from loamy sand to clay loam with an even distribution of the different sand fractions. With 13 to 26 % the silt contents are higher than in the previous profiles. The bulk density of the reference profile is 1.65 g cm^{-3} in the topsoil and decreases to 1.4 in 50 cm depth. This is different to all of the previous profiles which exhibit high bulk densities throughout the entire profile. As in profile 25, the calcic horizon starts with nodules and shows a transition to a massive calcrete structure below 86 cm in depth.

The soil reaction is moderately alkaline in all horizons; the EC is of the same magnitude as the Epipetric Calcisol developed in a reddish coverlayer (profile 15, see above). The fine earth in the nodular crust of the deepest horizon is carbonate free, the other horizons display both nodules and fine distributed calcium carbonate. It cannot be decided whether the fine distributed calcium carbonate is the result of in situ pedogenic precipitation or of a particle mixing process transport with the solum. A transport would stress the colluvial character of the profile that is also underlined by the relatively high organic carbon contents (0.45 - 0.85 %) across the entire profile.

Total element contents are constant except for the increase of calcium and magnesium in the carbonate rich horizons above the nodular crust. With 3-10 $mmol_c\ kg^{-1}$ the content of water soluble ions is very low. The CEC is increasing from 60 to 100 $mmol_c\ kg^{-1}$ with depth (from top- to subsoil).

From the total iron content only 20 % are pedogenic oxides. In comparison to the reddish substrates of the Luvisols, which have similar total Fe concentrations, the difference in pedogenic oxide contents could indicate both, a different origin of the soil parent material and / or the restricted weathering due to buffering by calcium carbonate.

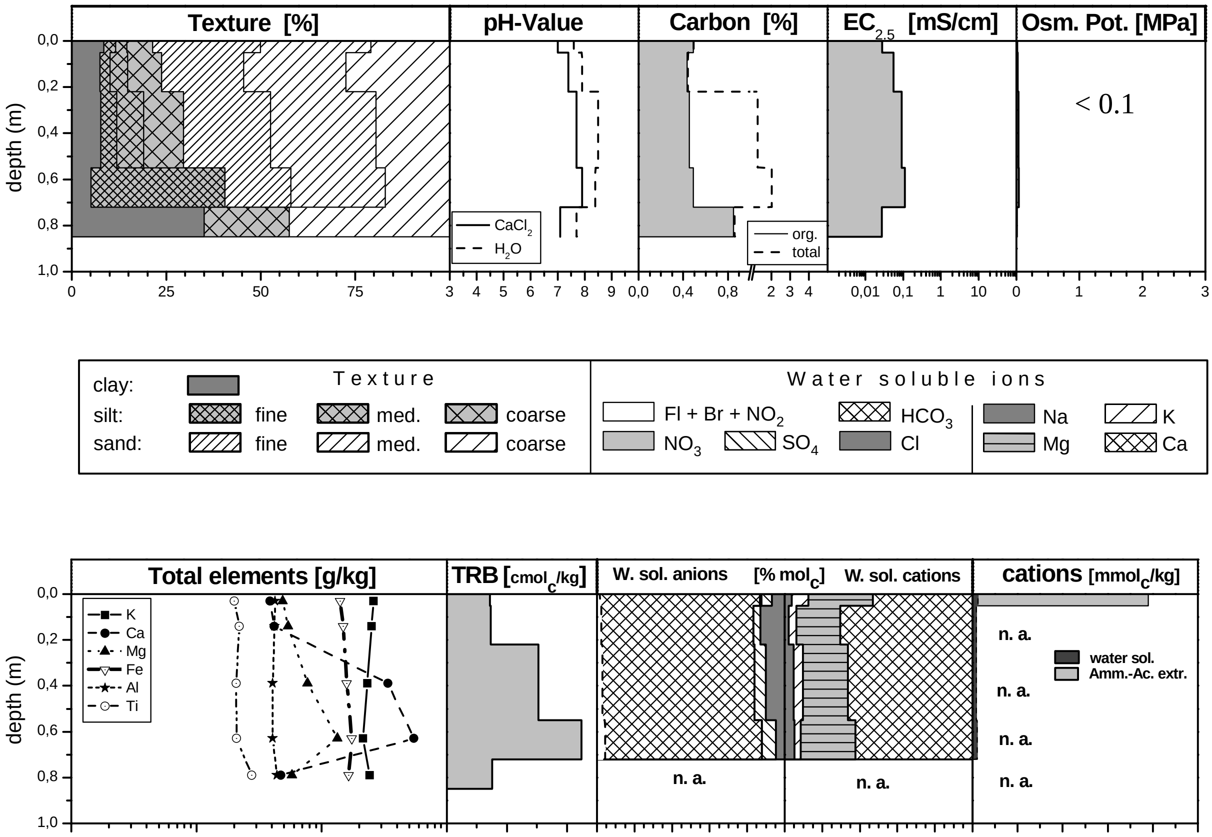


Figure 55 Properties of profile 8

3.4.3.4 Discussion of soil properties

With the exception of EC, the variability of most soil properties in this observatory is comparably high as indicated by Figure 56. The wide boxes also indicate an even distribution of the different site properties. For pH-values and clay & silt percentages the variability is nearly constant with depth whereas for EC the range is increasing and for organic carbon decreasing. Vertical variations within the profiles occur particularly in the organic carbon, decreasing with depth while clay and silt content reflect the typical increase.

The rooting space (RS) shows a wide variation ranging from 100 % in the deep developed Luvisols down to 3 % in the very shallow Epipetric Calcisols. All restrictions of the rooting space are caused by nodular or massive calcic horizons.

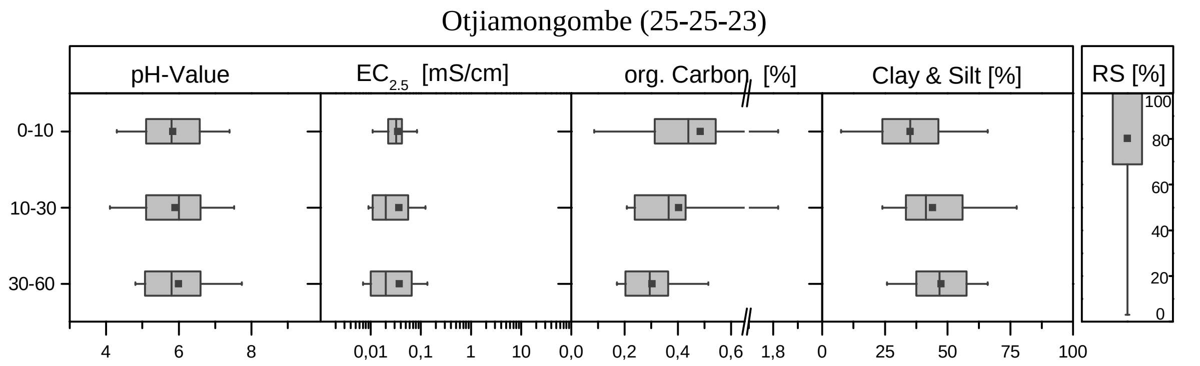


Figure 56 Variability of selected soil properties in three depth intervals for the observatory #05

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS= rooting space

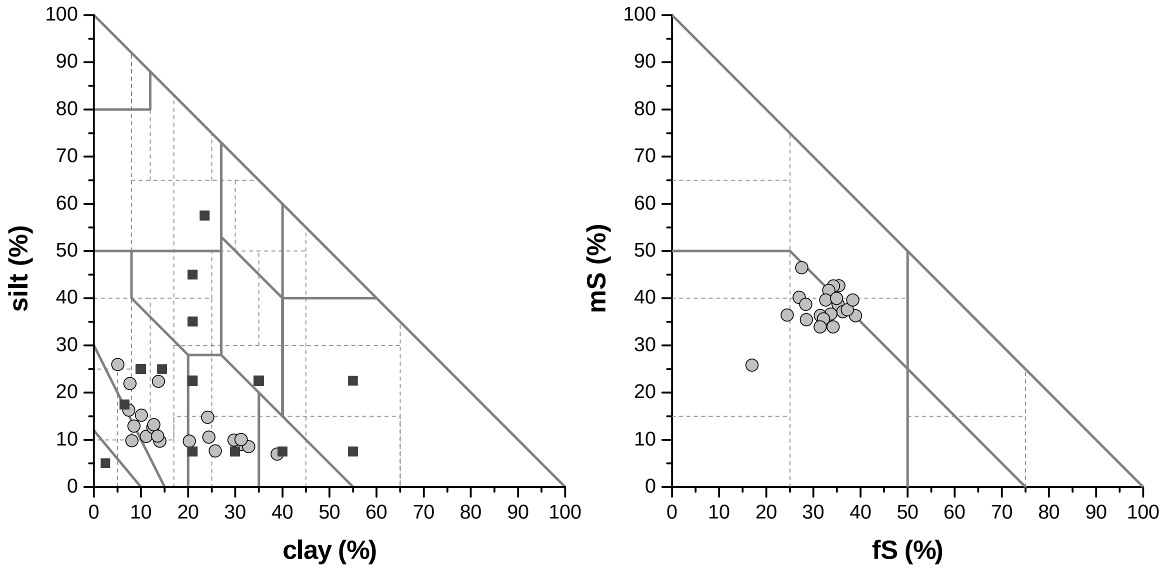


Figure 57 Results of the texture analyses for the observatory #05

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 57 provides the results of the texture analyses for the observatory #05. The sandy and clayey sandy character is dominant, only few samples examined by finger tests showed silt contents > 30 %. However, due to the presence of fine distributed calcium carbonate these tests were often difficult and may favour the silt content. Partly, the clay content exceeds 30 % meeting one requirement for vertic properties. X-ray diffraction analyses by WINTERSTEIN (2003) showed that the clay fraction contains only small amounts of smectite and is dominated by illite. Illite does not swell or shrink as smectites do, so the clay rich soils do not show deep cracks or slickensides. When these horizons are dry they do not show any signs of aggregation, instead one can find a homogenous concrete-like block which is not typical for Vertisols.

With regard to the sand fractions all analysed samples belong to the same cluster of coarse sand (gSfs, the outlier is produced by the presence of micro-nodules of calcium carbonate in the coarse sand fraction).

From an ecological point of view the observatory can be subdivided into three clusters: i) the eastern part with deeply developed clayey Luvisols which have slightly acid pH-values and a very low nutrient content, ii) the western part with loamier Calcisols and Cambisols with high pH-values, dark brown colour and higher content of organic carbon, and iii) shallow Calcisols in direct vicinity to the rivier which are restricted in the rooting depth and have neutral to alkaline pH-values. EC and organic carbon are higher in the Calcisols but the availability of some elements such as phosphor might be limited due to the high ph-values. Additional small scale variations of soil properties across all soil units are ascribed to the activity of the mound building termite *Macrotermes michaelseni*, except for the very shallow Epipetric Calcisols.

The genesis of the profiles cannot be explained for certain, an inherent problem of the polygenetic landscapes with their variable climatic history and mass movements of soil parent material since the tertiary. However, some observations and indications shall be summarised in the following.

It can be assumed that the Luvisol association is developed in a granitic derived soil parent material and that dispersion and translocation of clay is continuing with present pH-values and climatic conditions, appearing after strong rainfall events. Clay coatings are often observable in the subsoils. This translocation is probably also an important process in the further genesis of decaying termite mounds which initially exhibit homogenous clay contents across the entire mound profile. If we expect these decayed mounds to be scattered across the landscape for a long period of time and thus many positions should be influenced by the soil mixing caused by termites, decidedly less differentiated profiles should be found. However, the dominant matrix soils are Luvisols with a clay content increase around 20 % from topsoil to 100 cm depth and only few of the recently decayed mounds show the homogenous texture.

The profiles in the western part of the observatory and adjacent to the rivier are higher and deeper accumulated with organic carbon leading to the assumption that they are 'fluvial' deposited. Nevertheless, the origin of this material is not clear. One possible explanation is the accumulation of eroded topsoil material of the surrounding area. Another possibility is the development of more stable humus-complexes in soils with calcium carbonate and higher pH. During this study higher humus content and darker colour were frequently occurring features on soils influenced by calcic material. EITEL & EBERLE (2001, 2002) reported regions around 50 km north that display considerable proportions of soils with dark, mollic epipedons which they classified as Kastanozems. They assumed that these soils have been formed in earlier and more open and grass dominated periods and are now subject to degradation processes. It is possible that soils with a similar genesis exist in the study area.

The genesis of the petrocalcic horizons or calcretes cannot be discussed here. Main questions are the age of the calcretes, the kind of genesis (aeolic or phreatic input) and its relationship to the present landscape and soil situation. The topic is extensively discussed e.g. by EITEL (1994) and KEMPF (2003).

3.5 Observatory 06 (Okamboro)

3.5.1 Regional overview

Okamboro, a Herero community in the Ovitoto communal area, is located in the Otjotzondjupa region of central Namibia, approx. 30 km southeast of Okahandja within the landscape unit Windhoek bergland. The area records a mean annual rainfall of around 360 mm during the summer months from Sept. until April. Mean annual temperature is approximately 20°C. The region belongs to the highland Acacia savanna zone (MENDELSOHN et al. 2002).

Geologically, the region belongs to the Swakop group (Damara sequence, Kuiseb formation) characterised by mica schists. Although the height of 1500 m asl is comparable to the previous savanna observatories north of Okahandja, the topography is more differentiated and strongly affected by the dissection of small riviers which drain north into the Swakop river. Few km towards the east, higher mountains with heights up to 1700 m asl characterise the hilly to mountainous structure of the area. Major landforms are undulated plains, hills and rocky outcrops.

The Hereros are traditional cattle farmers and livestock husbandry is the most important form of land-use. The most important pressure on the environment is overgrazing which leads to a shift in natural vegetation (e.g. bush encroachment) and enhances the erosion risk of the shallowly developed soils.

3.5.2 Observatory description

The observatory #06 Okamboro is situated few kilometres south east of the village Okamboro in a preferred grazing area. The mean height is 1500 m asl with a variation of only 12 m within the site. Several riviers dissect the area and drain the system towards the northwest (Figure 58).

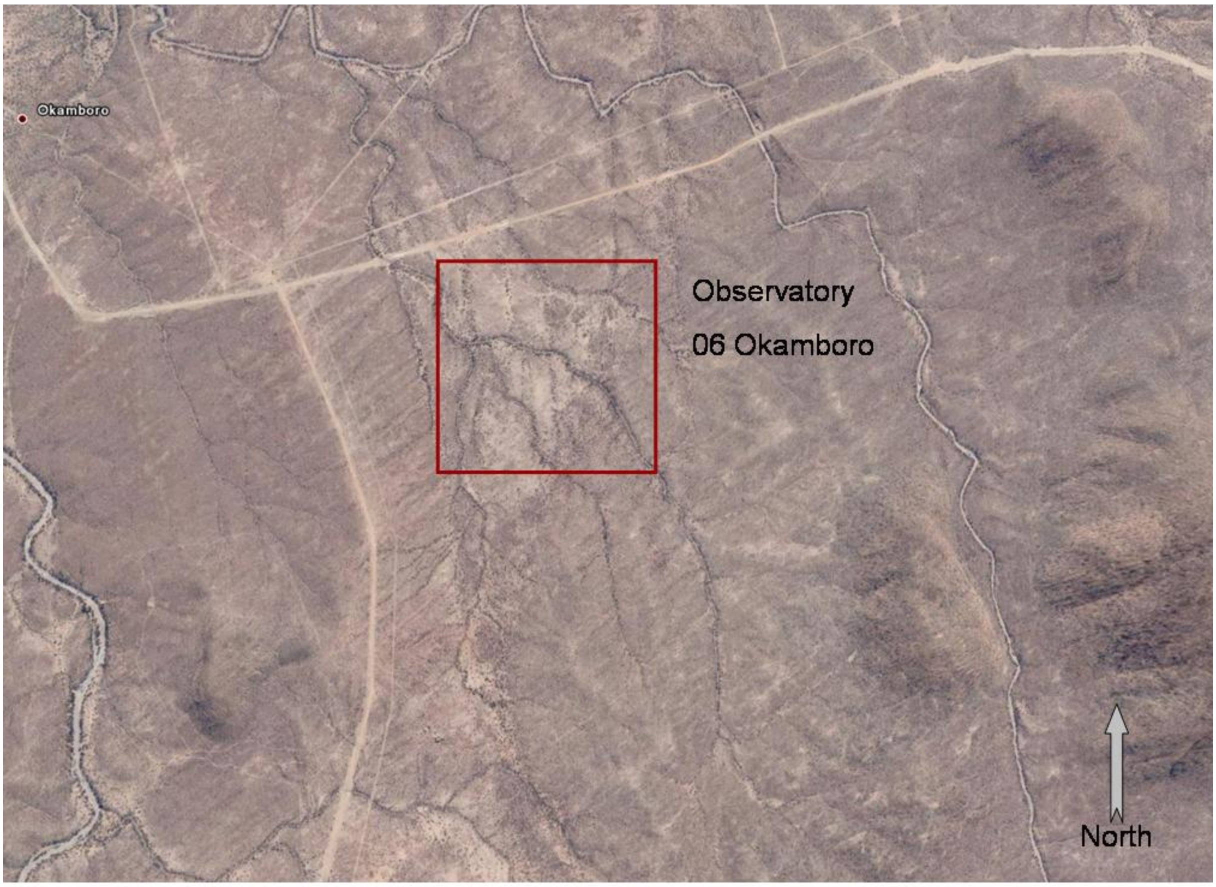


Figure 58 Aerial picture of the observatory # 06 Okamboro (source: Google Earth)

The dominance of the topography is reflected in the habitat description of the observatory: i) hills with outcrops, ii) gently undulating plains and iii) dissected plains. The rocky outcrops and underlying bedrock consist of the mica schist with quartz veins.

The vegetation is a transition from Thornbush to Bergland Savanna (MENDELSOHN et al. 2002) The dominant species in the grass layer is *Schmidtia kalahariensis*, an indicator for overgrazing. *Catophractes alexandri*, *Acacia reficiens* and *Acacia mellifera* are the dominant bushes.

3.5.3 Soils

3.5.3.1 Main soil units

According to the standardised sampling scheme, 27 soil profiles were investigated, analysed and classified according to the WRB (1998). On the observatory the reference groups Regosol, Calcisol, Cambisol and Leptosol were found. The relatively high variety of soil types is not evenly distributed. In Figure 59 the regional distribution and in Figure 60 the frequency distribution is given on a two qualifier level. With 77 % Regosols are the most dominant soil units, the other reference groups are only represented by few profiles.

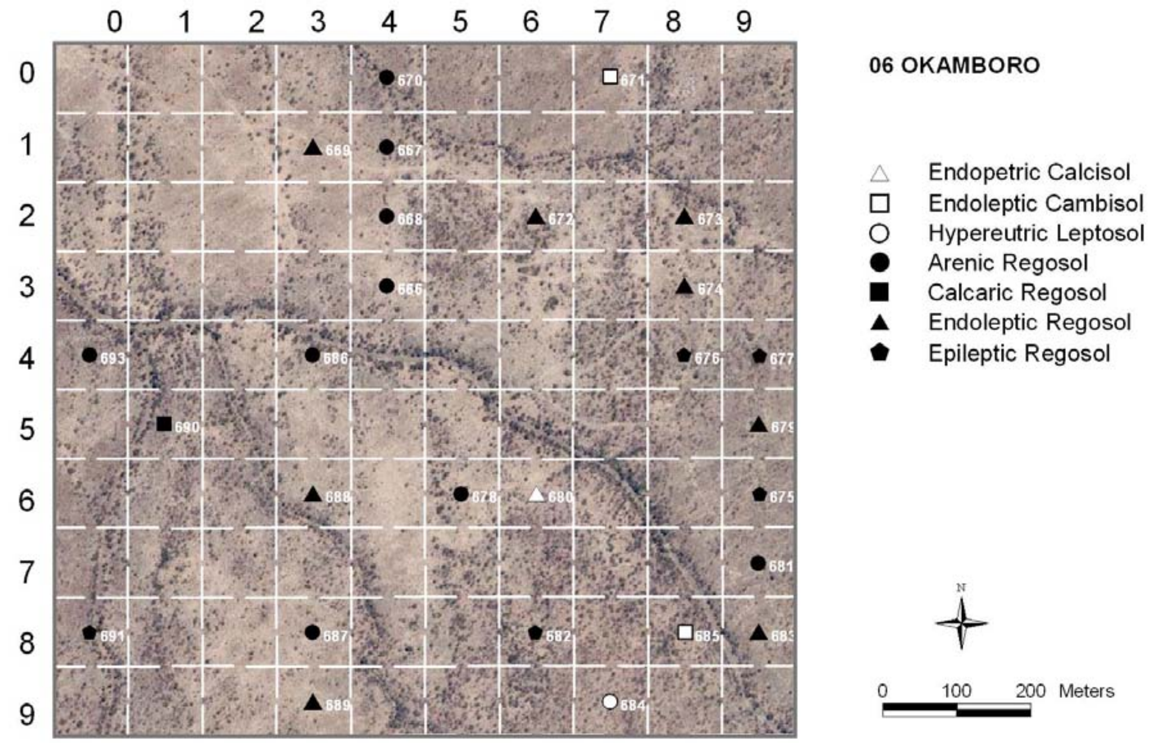


Figure 59 Distribution of soil units (WRB 1998, 1st qualifier level) on the obs. #06 (Okamboro)

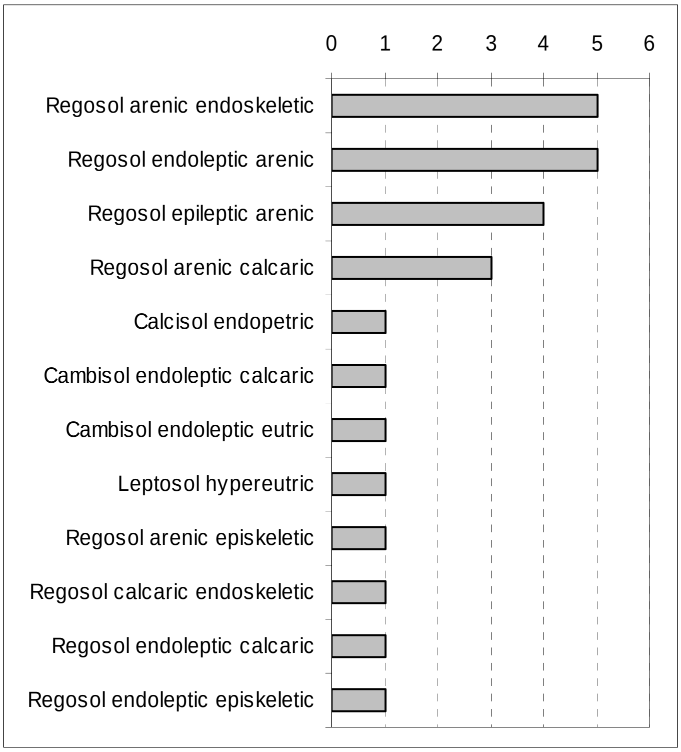


Figure 60 Frequency distribution of WRB (1998, 2nd qualifier level) soil units in obs. #06

The key factors for the soil properties and the classification units in this observatory are type of substrate, depth of the profiles and content of coarse fragments. Especially the latter two vary over short distances and are responsible for the almost random distribution of soil units. One visible trend in the dominating unit is the occurrence of Endoskeleti-Arenic Regosols in the northwestern and central part of the observatory, reflected by the lighter colours in the aerial photograph. In the eastern part more shallow Areni-Leptic Regosols occur.

3.5.3.2 Remarks on classification

The soil units are classified according to the WRB (1998) nomenclature. The most important features as well as the differences between the soils (texture, content of coarse fragments, depth of bedrock layer,) could be described satisfactorily with the units and assigned qualifiers. By additionally applying the prefixes epi and endo, for the Regosols a much better differentiation of the soil physical properties is possible. This enables a very detailed naming of the soil units.

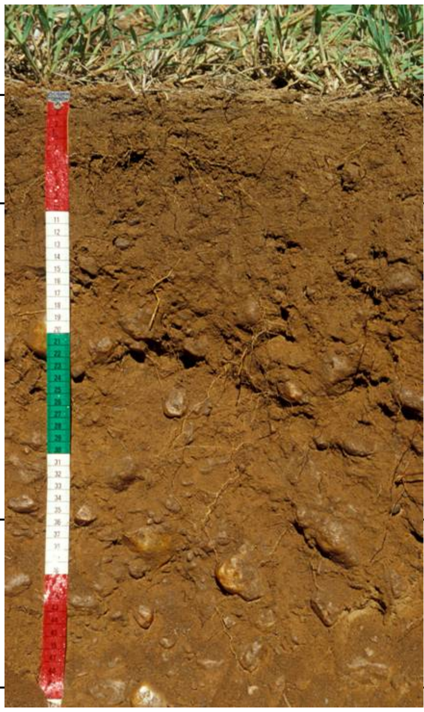
With regard to soil genesis it would also be appropriate to classify many of the Regosols as Cambisols, however, the texture requirements are fulfilled only in two profiles of the observatory.

By applying the new version of the WRB (2006) only minor changes were necessary. None of the criteria of the newly introduced qualifiers were fulfilled. Several changes were made in the ranking of qualifiers which lead to a higher importance of ‘Eutric’ and ‘Dystric’ and a lower importance of ‘Arenic’ and other texture-related qualifiers.

3.5.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **666**	Ha: **34**	Classification (WRB 1998)	**Episkeleti-Arenic Regosol (Eutric)**
		(WRB 2006)	**Haplic Regosol (Eutric, Episkeletic, Arenic)**



cm	Horizon	Description
		low penetration resistance (dry)
0–10	Ah	Loamy sand (Su2) with fine sand (fS), 5% fragments, single grain to subangular blocky structure, grey-brown, Munsell 10YR5/4 dry and 10YR3/3 moist, 21-50 roots/dm^2, moist, low excavation difficulty
10–35	Bw1	Loamy sand (Sl2) with fine sand (fS), 60% fragments, single grain structure, grey-brown, Munsell 10YR5/4 dry and 10YR3/3 moist, 21-50 roots/dm^2, dry, moderate excavation difficulty
35–50	Bw2	Loamy sand (Sl2) with fine sand (fS), 70% fragments, single grain structure, grey-brown, Munsell 10YR5/4 dry and 10YR3/3 moist, 21-50 roots/dm^2, dry, moderate excavation difficulty → BC Transition to saprolith / continuous bedrock

Figure 61 Description of profile 666

The Episkeleti-Arenic Regosols are a typical example for the slightly deeper developed soils in the plain habitats. The transition zone to the saprolithed bedrock occurs at approx. 50 cm. In this profile a high quartz pebble content dominates the coarse fragments. This is a typical residual of quartz veins which are part of the mica schists and resist weathering processes leading to an accumulation of quartzes in the soils as well as on the soil surfaces.

The texture of the fine earth is loamy sand, dominated by fine sand and coarse silt with a slight increase of clay content in the subsoil. The soil reaction is slightly acid across the entire profile. The organic carbon reaches ~ 0.35 % in the topsoil and shows a marginal decrease with depth. EC is low with highest values in the topsoil.

Total element contents are constant across the profile depth and the TRB is relatively high with around 230 $cmol_c\ kg^{-1}$. The content of water soluble ions is very low with 3-5 $mmol_c\ kg^{-1}$ and the extractable bases reach highest values in the subsoil.

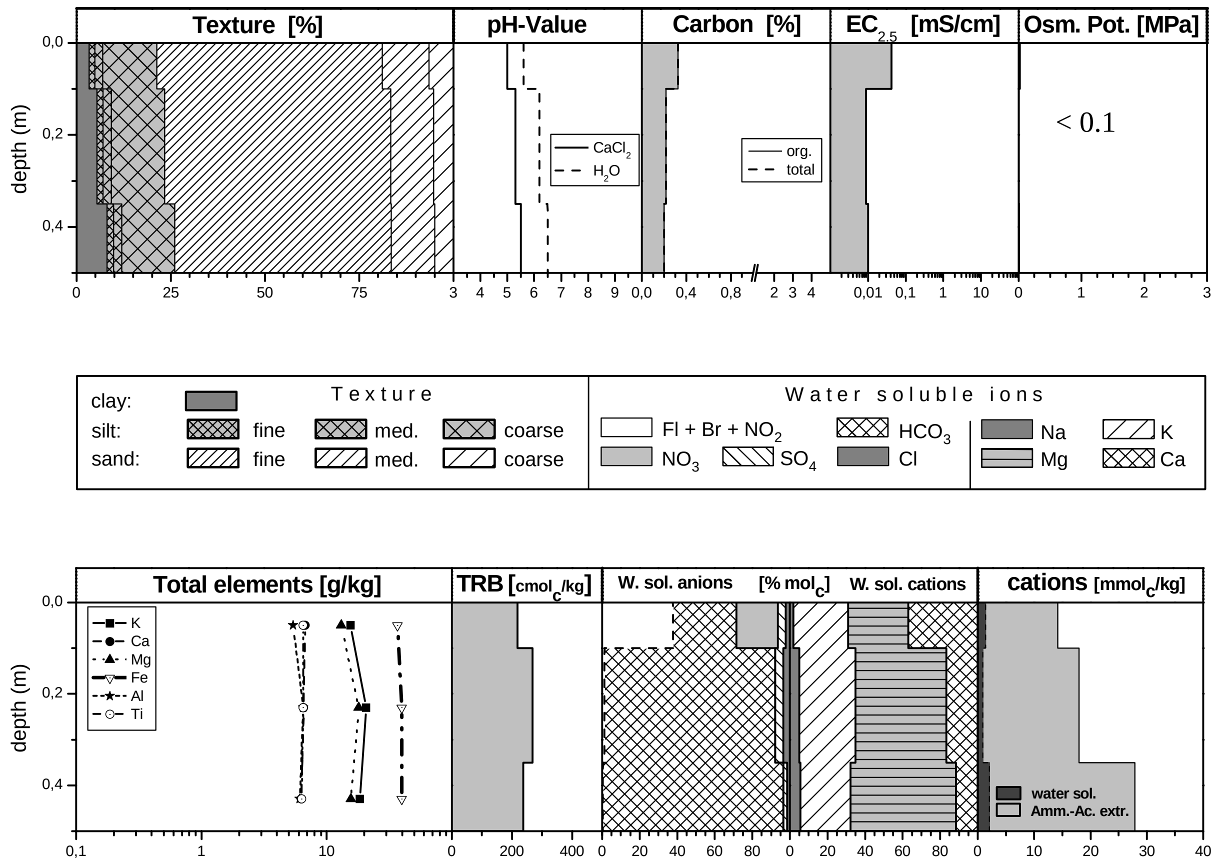


Figure 62 Properties of profile 666

Reference profile # 2

Profile: **676**	Ha: **48**	Classification (WRB 1998)	**Areni-Endoleptic Regosol (Episkeletic Hypereutric)**
		(WRB 2006)	**Epileptic Regosol (Hypereutric, Episkeletic, Arenic)**

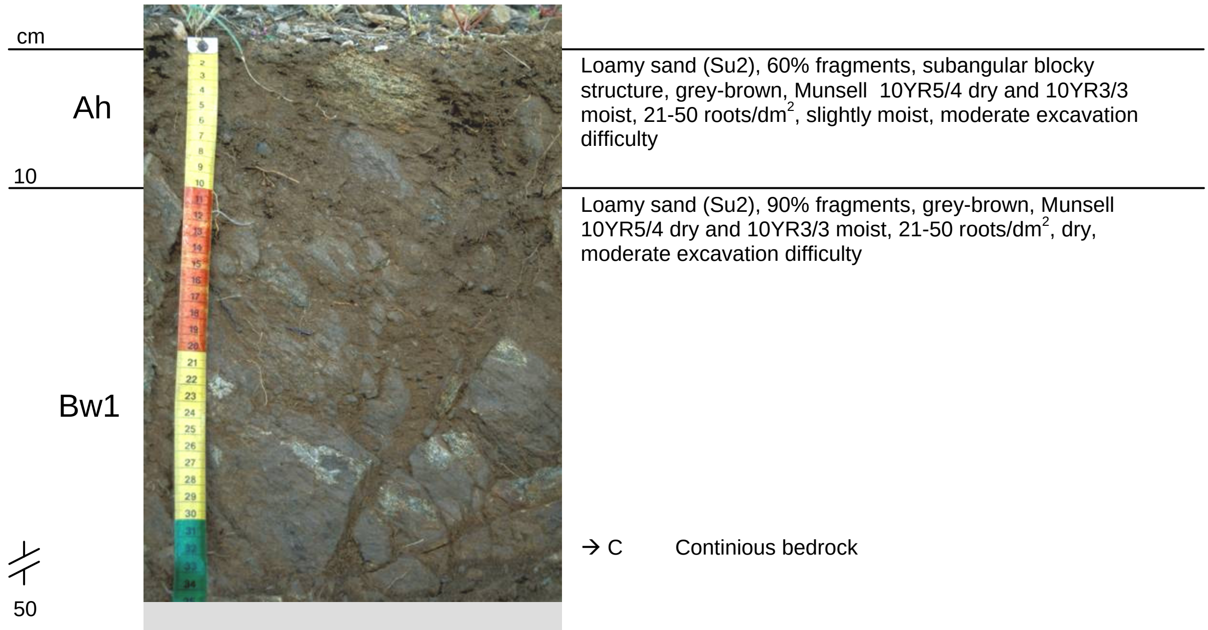


Figure 63 Description of profile 676

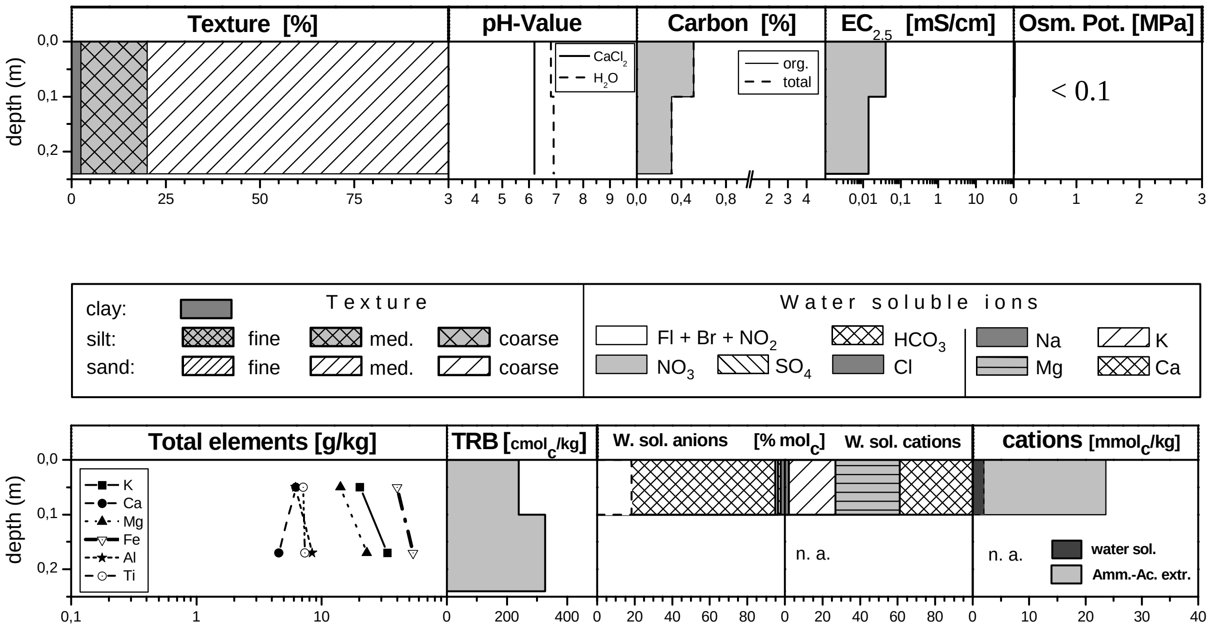


Figure 64 Properties of profile 676

The Areni-Endoleptic Regosol is an example for a soil in the undulated plain and hill habitats developed in a shallow cover layer above the saprolitic bedrock. In this profile the transition zone to the saprolith already occurs at approx. 10 cm. The topsoil horizon exhibits high contents of coarse fragments (60 %) which are partly saprolitic and still show structures of the mica schist. The mica schist is found as continuous bedrock below 50 cm. Within this profile no quartz pebbles occur.

The soil properties are almost similar to the previously described profile except for the neutral pH-value, a higher content of organic carbon and a higher TRB value in the second horizon which is a result of the lower weathering status of the saprolith.

3.5.3.4 Discussion of soil properties

The variability of soil properties in this observatory is shown in Figure 65. The most important variations occur in the pH-values and in the rooting space which is driven by the depth of bedrock layer and the content of coarse fragments. For the topsoil the variability of fine grained particles (clay & silt) is rather low. Few vertical trends are evident, except for the slight decrease of organic carbon and the lower silt and clay contents in the topsoils which may be a result of deflation.

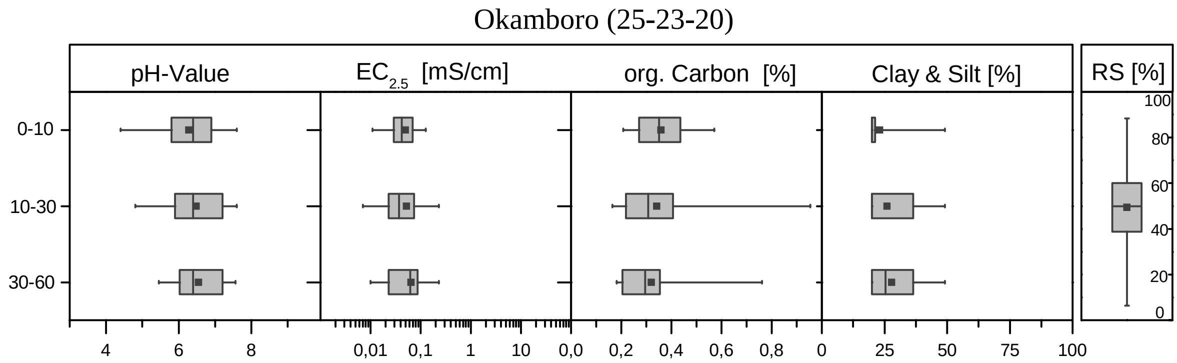


Figure 65 Variability of selected soil properties in three depth intervals for the observatory #06

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

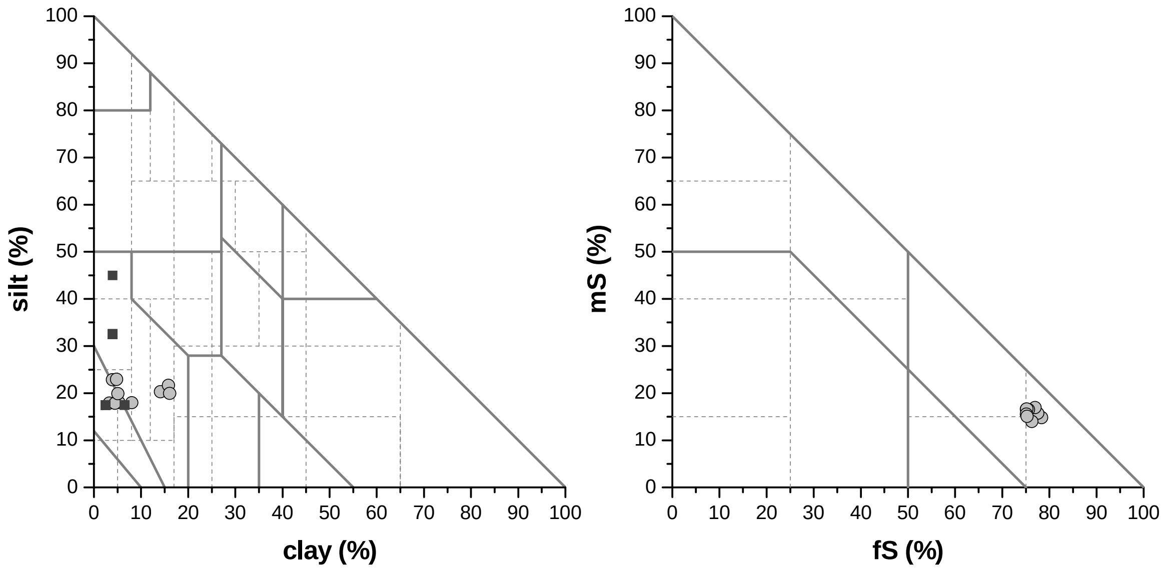


Figure 66 Results of the texture analyses for the observatory #06

Squares = finger test (all samples) and circles = lab analyses (selected samples)

For the observatory #06 the sandy and silty character is dominant (Figure 66), only few samples of the Cambisols show more than 10 % clay. With regard to the sand fractions, the 10 analysed samples display a remarkable homogenous composition with a strong fine sand dominance. This is an indication for a very homogenous structure and weathering of the mica soil parent material. I assume that the content of coarse fragments and the depth of the bedrock is the main differentiating factor for plant growth. The different states of soil reaction may be an additional ecologically important factor but the texture driven water supply seems to override this. Structural differentiation of the vegetation occurs in form of more open grass dominated sites and denser bush patches with partly higher species diversity. The highest bush and tree densities are found along the riviers but also in smaller drainage lines which developed in northeast to southwest direction along the micro-faults of the mica schist. They obviously provide more water. An additional effect might be the micro topography and the depth of bedrock which leads to small scale run-off / run-on situations causing uneven water distribution. The grassy plains consist of a more homogenous soil structure which provides a more even water availability. This might be responsible for the higher proportion of grasses, in particular *Schmidtia kalahariensis*, and the shrub *Catophractes alexandri*. *Schmidtia kalahariensis* is well known as a sign for overgrazing in this area. Next to the problem of degradation of grazing quality the risk of soil erosion increases strongly due to the reduction of the cover of perennial species. Additionally, the fine sand and coarse silt dominated textures are highly vulnerable to water erosion. Also the short distances to the riviers reduce the probability that the material will only be relocated within the area. During the study main erosion features were moderate rill and slight sheet erosion signs.

3.6 Observatories 39 (Nareis) and 40 (Duruchaus)

3.6.1 Regional overview

The observatories #39 (Nareis) and #40 (Duruchaus) are located in the Khomas region, approx. 25 km northwest of the town Rehoboth. The area records a mean annual rainfall of around 200-250 mm during the summer months from September until April. Mean annual temperature is around 18-20°C. The region is situated in the transition zone of three major biomes, the Nama Karoo with dwarf shrub savanna in the south, the Highland or Mountain savanna in the north and the Southern Kalahari in the west (MENDELSOHN et al. 2002).

Geologically, the region belongs to the Duruchaus Formation of the Nosib group (Damara Sequence) characterised by mica schist and calcareous schist. The wider area around the observatories is flat to slightly undulated with a mean height of 1650 m asl, the nearest mountains with heights up to 2000 m are in approx. 10 km distance in northern and southwestern direction. The topography is only weakly differentiated, main features are the dissections by small riviers which drain into the Oanob rivier. An azonal feature characterising the landscape around the observatories is the shallow occurrence of calcrete which prevents the growth of a more bush dominated vegetation type typical for the wider region.

Typical land-use in the area is cattle, sheep and goat farming in varying intensities. Detailed information about the farming history in the area which is characterised by relatively small farms is provided at www.biota-africa.org (→ Nareis / Duruchaus → Socioeconomy).

3.6.2 Observatory description

The observatories are located directly west of the Oanob river on two farms (Nareis and Duruchaus) separated by a fence (Figure 67). Texture and composition of the vegetation on Nareis and Duruchaus differ from that of surrounding farms which is due to specific soil conditions, i.e. the shallow and calcareous character which obviously prevents the growth of trees and larger bushes. The vegetation on the two observatories is typically dominated by dwarf shrubs like *Leucosphaera bainesii, Aizoon schellenbergii, Pentzia calva, Pteronia species* and perennial grasses like *Stipagrostis obtusa, Stipagrostis ciliata* and *Fingerhuthia africana*. Phanaerophytic shrubs (e.g. *Catophractes alexandri, Acacia mellifera, Rhigozum trichotomum*) and trees (e.g. *Acacia erioloba*) are either very scattered or restricted to certain habitats like drainage lines and the edges of pans on Nareis (www.biota-africa.org).

Nareis and Duruchaus underwent great differences in grazing type (animals) and intensity over the past several decades. Whereas cattle and horses with 10-12 ha/LSU (life stock unit) were stocked on observatory #40, on #39 dominantly sheep with 17-20 ha/LSU were responsible for the grazing impact in the past (www.biota-africa.org). This led to a distinct composition of plant species as well as a varying dominance of biotic soil crusts. Differences in the spectral reflectance are clearly visible on the satellite image (Figure 67)

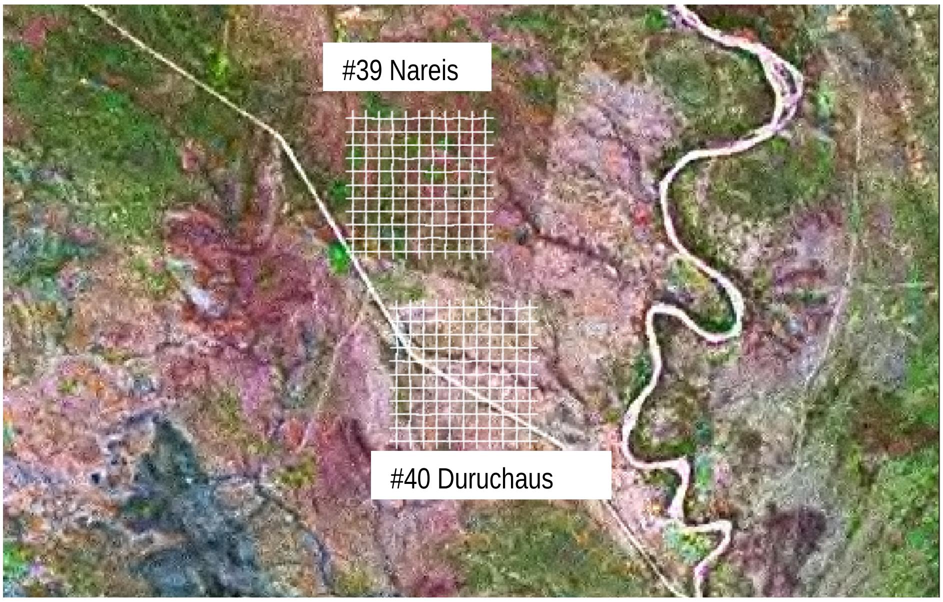


Figure 67 Satellite image of the observatories #39 and #40 (Landsat TM image © Nasa)

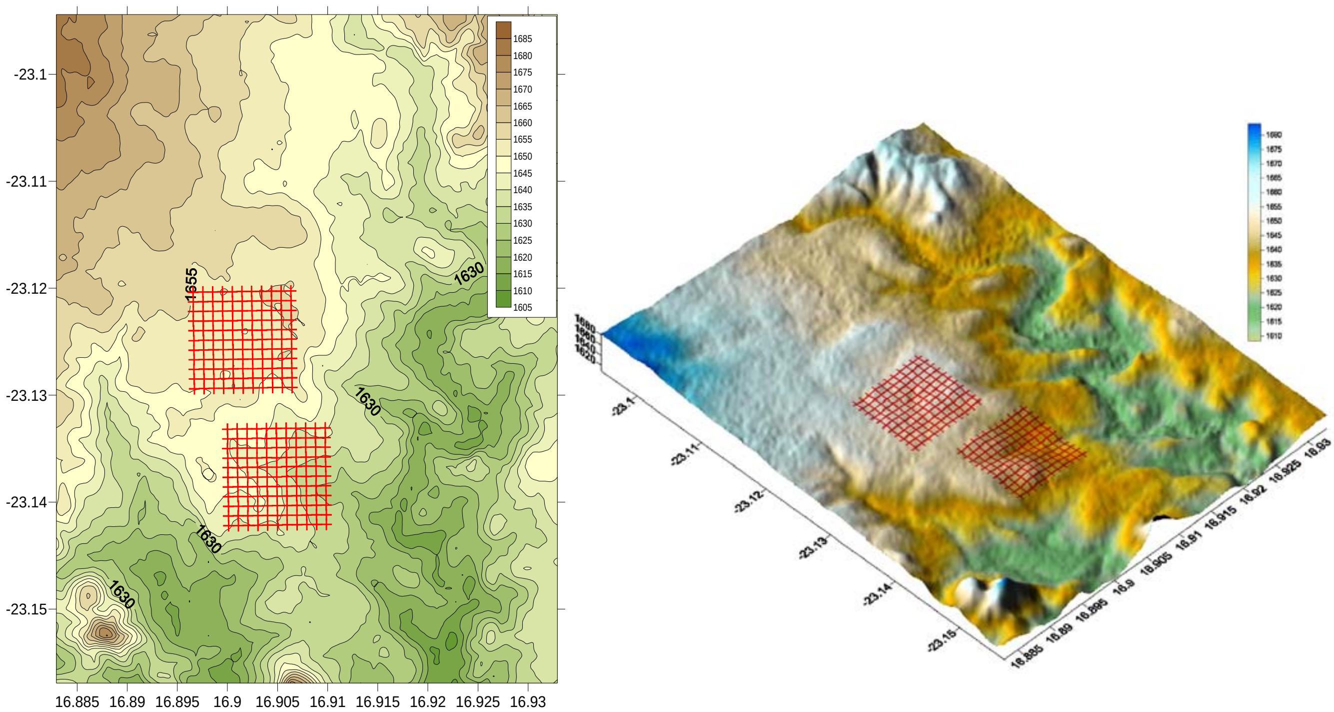


Figure 68 Elevation models of observatories #39 & #40

The mean height of 1650 m asl varies only slightly within the observatories except for a few rivier structures in the southeastern part of Duruchaus. The topography of the observatories and their surrounding is shown in Figure 68. Several smaller riviers dissect the area and drain the system towards the east to the Onaob rivier.

The habitats were named by vegetation structure and topography as i) chamaephytic shrubland plains, ii) grassy plains, iii) drainage lines, and iv) pans or vleis the latter only found on Nareis.

3.6.3 Soils

3.6.3.1 Main soil units

On each observatory 25 soil profiles were investigated. Following the WRB (1998), a comparatively high number of reference groups (Calcisol, Leptosol, Regosol and Luvisol) were found, which are, however, very unevenly distributed.

Figure 69 shows the spatial distribution of soil units. The soils on the observatories Nareis and Duruchaus are mainly characterised by the occurrence of a calcrete layer or petrocalcic horizon which leads to the dominance of Calcisols on both observatories. Epipetric Calcisols are the dominant soil unit found on the plains. The petrocalcic horizon is 20-40 cm thick and followed by a calcareous sandstone saprolith. In parts where the rivier dissection leads to erosion of the petrocalcic horizon or a loose calcrete structure is evident, Endoleptic Calcisols occur which are characterised by a contact zone to the underlying sandstone and a high content of finely distributed calcium carbonate. In strongly eroded sections these units are associated with shallow Leptosols.

A unique soil unit is the Cutanic Luvisol only found in pan situations on the Nareis observatory. These heavy textured profiles are free of coarse fragments and show signs of clay movement and clay enrichment.

A common feature of both observatories is the strongly developed, black biological soil crust (BSC). The combination of high radiation due to low plant cover and the presence of calcium carbonate in the substrate seem to favour growth of these crusts. Both sites have therefore a strong BSC cover and a dark soil surface. Although coverage of BSC in both observatories is comparable, the more recent satellite and aerial pictures (see Figure 67 & Figure 69, 1997 photo) show a distinct colouring of the sites separated by the fence. It is assumed that the combination of stronger development of BSC (lichen crust with microstructure) and a higher percentage of small grass tussocks cause the darker colours on Nareis.

In Figure 70 the frequency of soil units on a two qualifier level is given. Calcisols are the most dominant soil units, the other reference groups are represented by only 6 (#39 Nareis) or 2 (#40 Duruchaus) profiles.

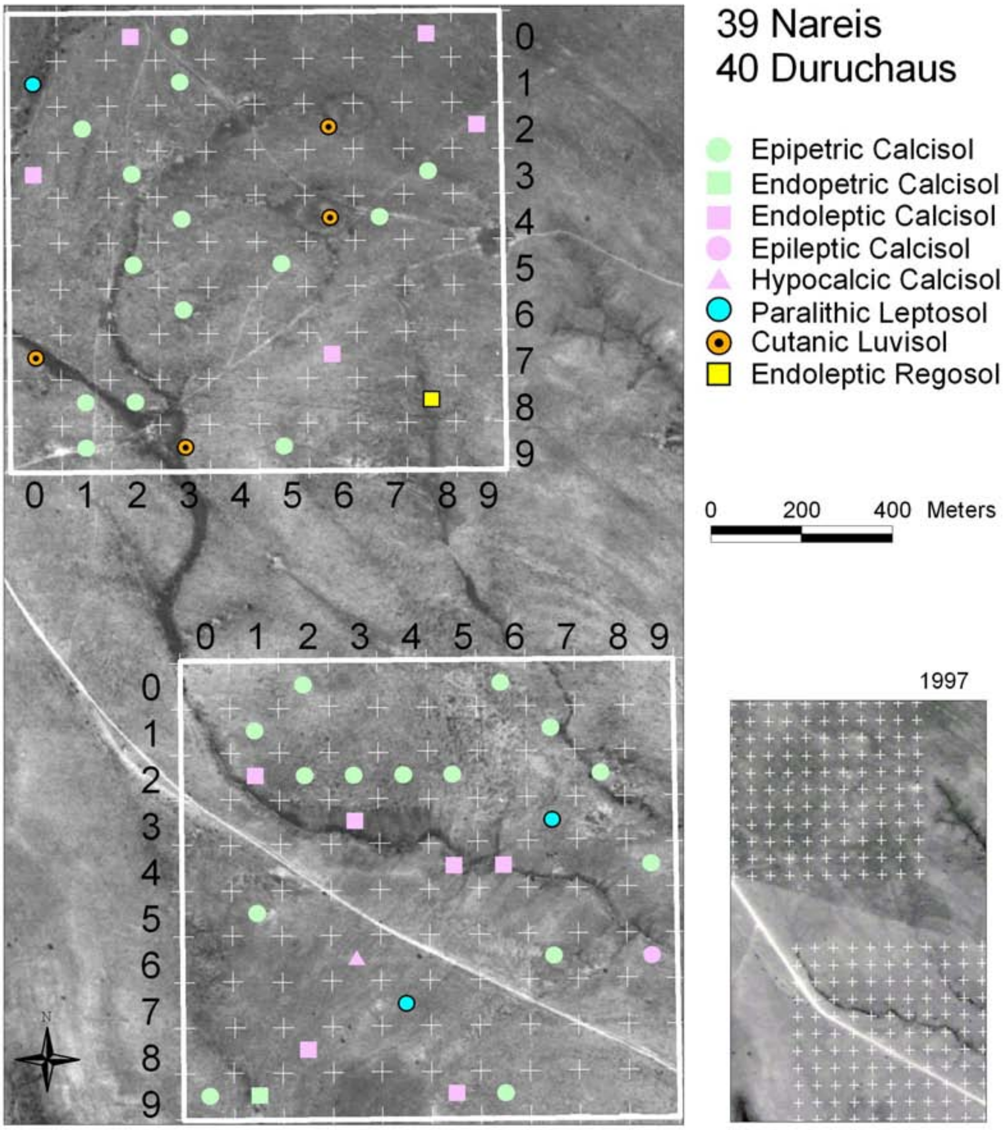


Figure 69 Distribution of WRB (1998, 1st qualifier level) soil units on the observatories #39 and #40 (plotted on aerial photograph from 1967)

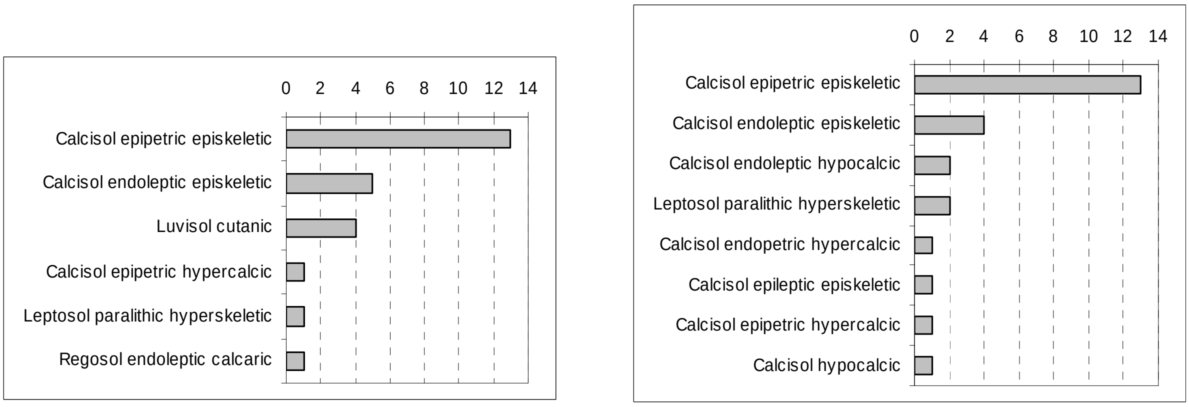


Figure 70 Frequency distribution of WRB (1998, 2nd qualifier level) soil units in the observatories #39 (Nareis, left) and #40 (Duruchaus)

3.6.3.2 Remarks on classification

Important soil features and the differences between the soils (calcic and petrocalcic horizons, content of coarse fragments, depth of bedrock) could be assigned appropriately to the soils with the reference units and the qualifiers according to the WRB (1998). A strong differentiation of soil physical properties in the Calcisols is possible when using the prefixes ‘epi’ and ‘endo’ additionally, which helps characterising the probably most significant ecological factor in these observatories, the depth of the petrocalcic horizon. This drives the thickness of the overlying substrate as rooting and water storage space. This, however, cannot be distinguished between depths of 0-50 cm in the current classification.

The application of the new version of the WRB (2006) reveals only minor changes. No new introduced qualifiers were fulfilled and only few changes were made in the qualifier ranking.

3.6.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **1219**	Ha: **51** Obs. **40**	Classification (WRB 1998) (WRB 2006)	**Episkeleti-Epipetric Calcisol (Hypercalcic)** **Hypercalcic Epipetric Calcisol (Episkeletic)**

cm	Horizon	Description
		Patches of BSC, 30 % gravel cover
0–14	Ah	Sandy loam (Su3) with fine sand (fS), 50% fragments, subangular blocky structure, extremely calcareous, brown, Munsell 10YR5/5 dry and 10YR3/4 moist, 30 roots/dm^2, moderate excavation difficulty
14–27	Bwkc	Sandy loam (Su3) with fine sand (fS), 50% fragments, subangular blocky structure, extremely calcareous, brown, Munsell 10YR6/4 dry and 10YR3/6 moist, 30 roots/dm^2, moderate excavation difficulty
27–28+	Bwkcm	Petrocalcic horizon, 98% massive to nodular crust, extremely calcareous

Figure 71 Description of profile 1219

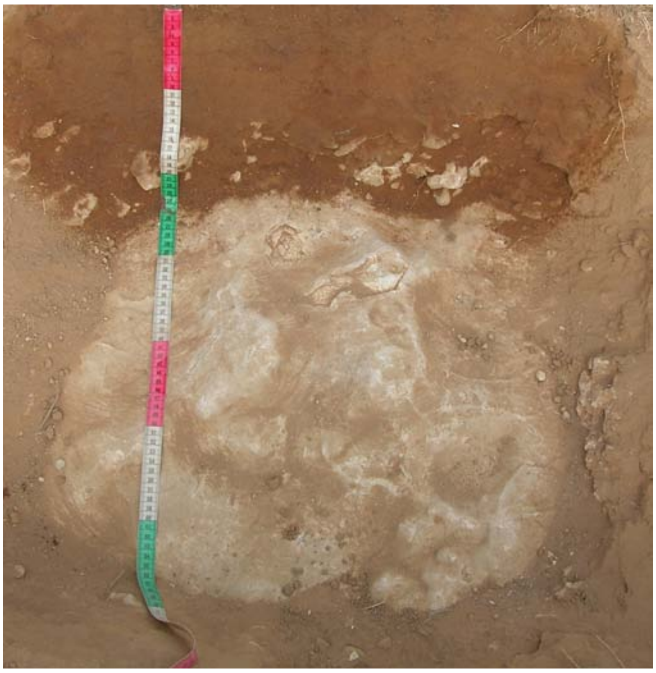


Figure 72 View of the sealed, laminar surface of the petrocalcic horizon

The Episkeleti-Epipetric Calcisol is a typical example of a soil in the plain habitats with a massive petrocalcic horizon in the upper 50 cm. There is a continuous transition into the group of Endoleptic Calcisols which only have a nodular calcic horizon that allows a penetration of roots. In the case of the Petrocalcic Calcisols such root penetration is not possible as the massive calcretes often have a laminar surface as shown in Figure 72.

The transition zone to the petrocalcic horizon starts at approx. 28 cm. In this profile, a high content of calcretes nodules dominates the coarse fragments.

The texture of the fine earth is sandy loam dominated by fine sand and coarse silt. The soil reaction is moderately alkaline across the entire profile and the organic carbon reaches ~ 0.8 % while the EC is low.

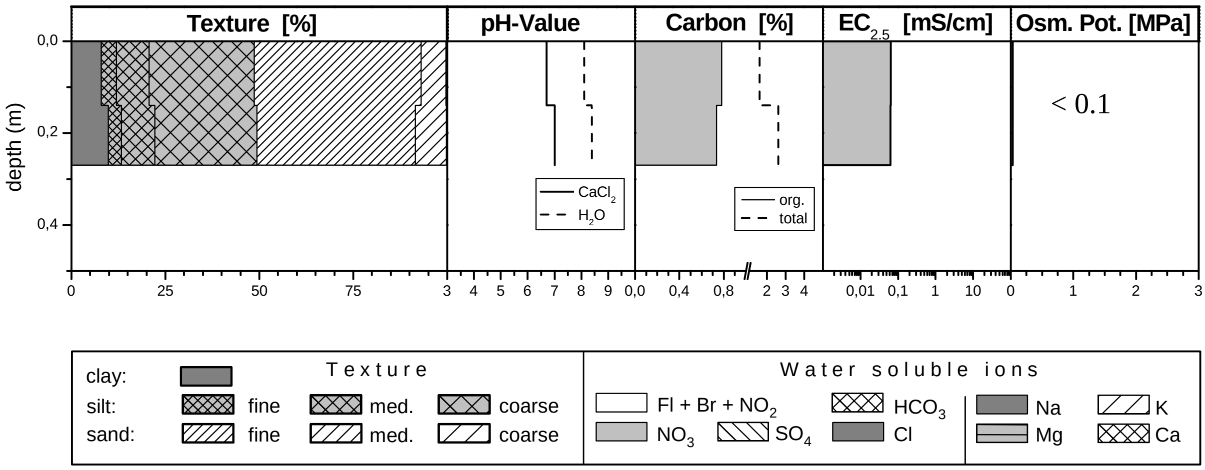


Figure 73 Properties of profile 1219

Reference profile # 2

Profile: **1243**	Ha: **02** Obs. **39**	Classification (WRB 1998) (WRB 2006)	**Episkeleti-Epipetric Calcisol (Hypercalcic)** **Hypercalcic Epipetric Calcisol (Episkeletic)**

cm	Horizon	Description
0		Patches of BSC, high penetration resistance (dry)
0–16	Ahkc	Sandy loam (Su3) with fine sand (fS), 75% fragments, subangular blocky structure, extremely calcareous, grey-brown, Munsell 10YR5/5 dry and 10YR3/5 moist, 20 roots/dm², moderate excavation difficulty
16–27	Bwkcm	98% fragments, massive, cemented structure, extremely calcareous, 10 roots/dm²
27–38	Bwk1	Sandy loam (Su3) with fine sand (fS), 10% fragments, subangular blocky structure, extremely calcareous, brown-grey, Munsell 10YR6/5 dry and 10YR3/4 moist, 50 roots/dm², low excavation difficulty
38–55+	Bwk2	Loam (Slu) with fine sand (fS), 30% fragments, slightly cementated structure, extremely calcareous, light-brown, Munsell 10YR7/4 dry and 10YR5/8 moist, 5 roots/dm², moderate excavation difficulty

Figure 74 Description of profile 1243

These second Episkeleti-Epipetric Calcisols shall illustrate the soil properties below the petrocalcic horizon and is therefore also reference profile for the Endoleptic Calcisols which are found along the dissection structures and in locations with weaker developed calcretes.

Here, the thickness of the calcretes of 15 cm allowed a destruction of the petrocalcic horizon which does not have a laminar structure on the surface and shows several fissures filled by fine earth where a penetration of roots and the seepage of rainwater are possible. A remarkably high density of roots is found in the zone below the petrocalcic horizon indicating the availability of water in this zone. The horizons below the calcretes are developed in the saprolith of the sandstone which to some extent still has its original schistose structure.

Topsoil properties of the fine earth are comparable to the previous profile. Below the calcrete a strong increase in fine distributed calcium carbonate and a reduction in organic carbon is evident.

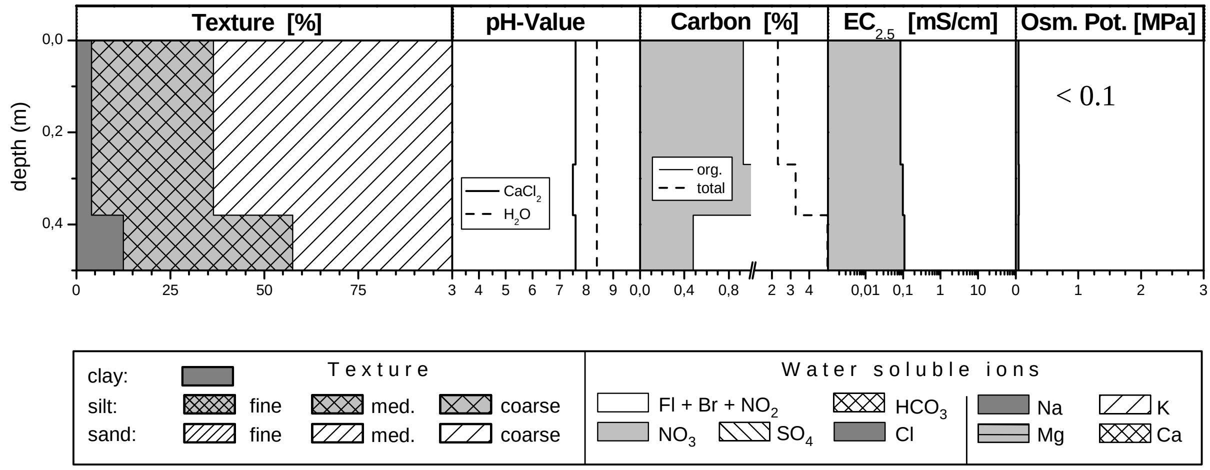


Figure 75 Properties of profile 1243

Reference profile # 3

Profile: **1244**	Ha: **46** Obs. **39**	Classification (WRB 1998) **Cutanic Luvisol** (WRB 2006) **Cutanic Luvisol**

No BSC, very high penetration resistance (dry)

cm	Horizon	Description
0–10	Ah	Loam (Slu) with fine sand (fSms), subangular blocky structure, dark brown, Munsell 10YR5/4 dry and 10YR4/3 moist, 2- 5 roots/dm^2, moderate excavation difficulty
10–25	Bwt1	Loam (Ls3) with fine sand (fSms), subangular blocky structure, dark brown, Munsell 10YR5/5 dry and 10YR3/3 moist, 2-5 roots/dm^2, moderate excavation difficulty
25–48+	Bwt2	Clay loam (Lts) with fine sand (fSms), 5% fragments, angular blocky structure, greyish-dark brown, Munsell 10YR5/5 dry and 10YR3/3 moist, 2- 5 roots/dm^2, moderate excavation difficulty

Figure 76 Description of profile 1244

The Cutanic Luvisol is a typical example for soils in the vlei habitats of the observatory Nareis. These soils differ strongly from the previously described Calcisols due to the deep substrate and the lack of coarse fragments and calcic horizons.

The texture is loam to clay loam with a marked clay increase with depth. In the subsoil clay coatings indicate a clay movement. The soil reaction is significantly lower than in the Calcisols with slightly alkaline pH-values; also the EC is lower than in the previous profiles. The entire profile is free of calcium carbonate which is probably responsible for the lack of BSCs.

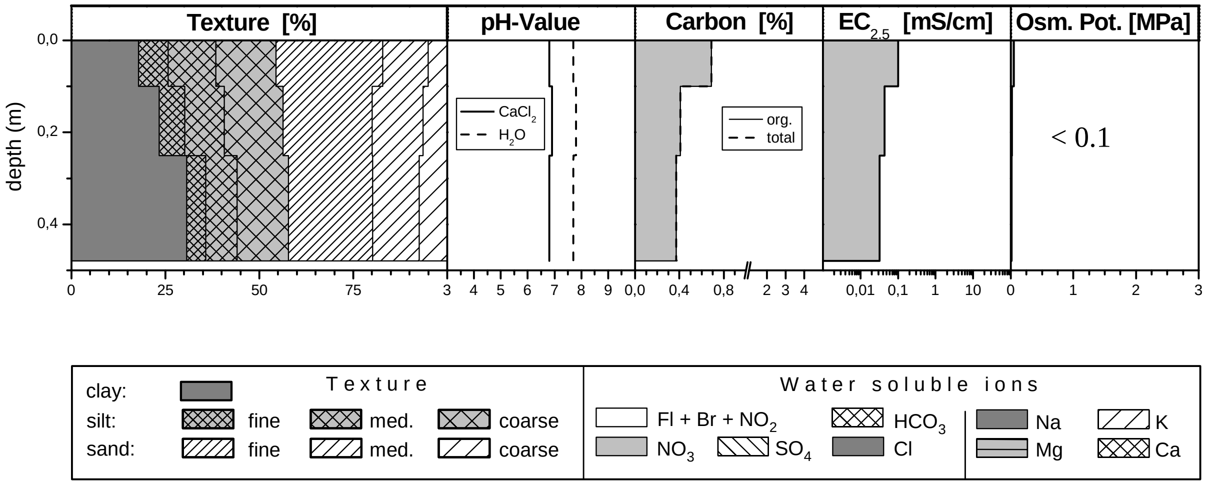


Figure 77 Properties of profile 1244

3.6.3.4 Discussion of soil properties

The variability of soil chemical properties in the observatories is low. Especially the pH-values and the EC display very low ranges, only the Luvisols sites in Nareis and a few calcium carbonate free topsoils have lower pH-values and enhance the range slightly. The most important variations occur in the organic carbon, the texture and the rooting space which is affected by the depth of calcretes and bedrock layer and the content of coarse fragments. Vertical differences in the profiles are relatively low, except for the slight decrease of organic carbon and the lower silt and clay contents in the topsoils.

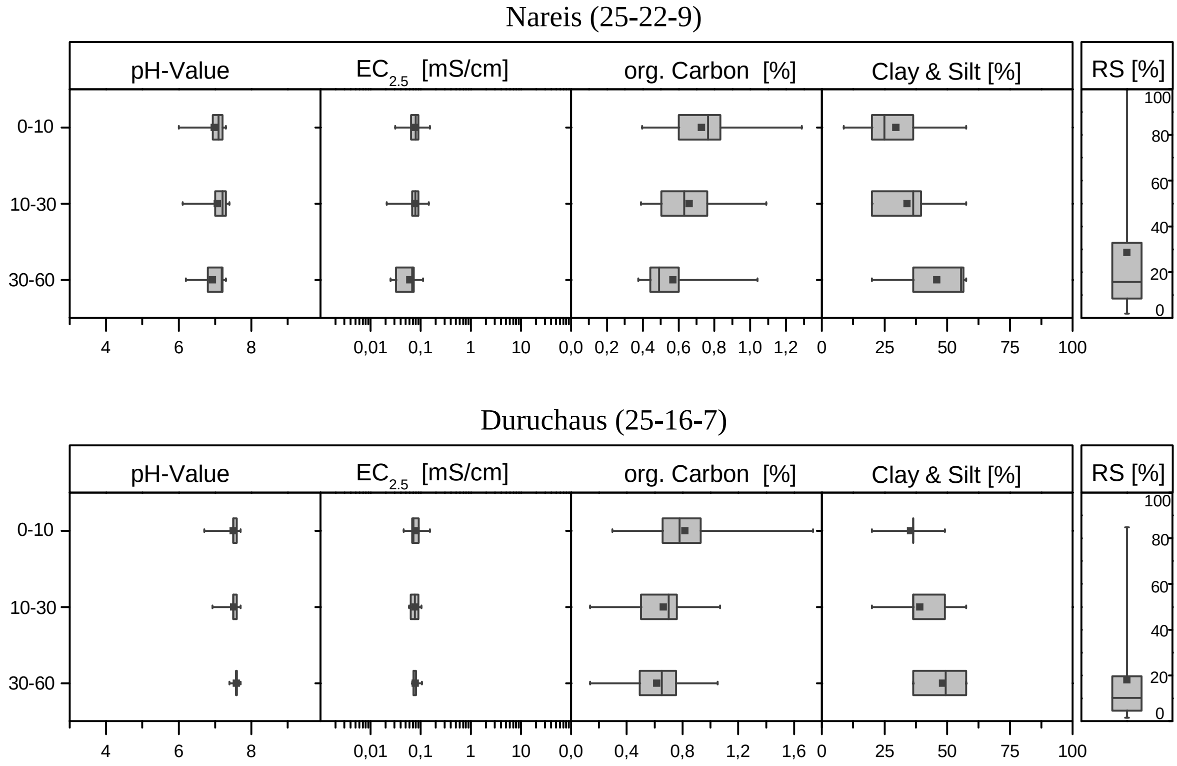


Figure 78 Variability of selected soil properties in three depth intervals for the observatories #39 and #40

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

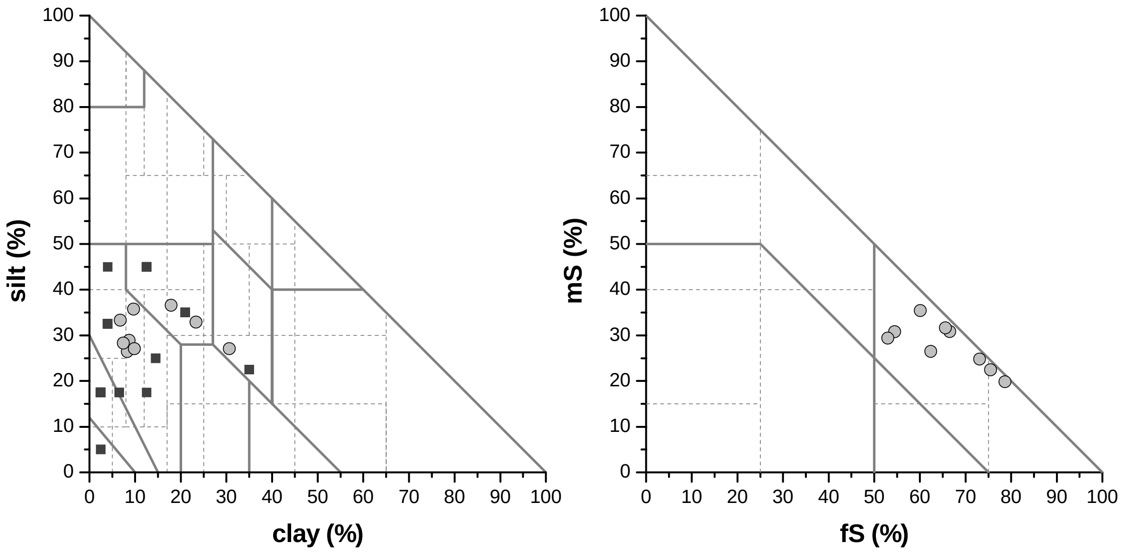


Figure 79 Results of the texture analyses for the observatories #39 and #40

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 79 shows the results of the texture analyses of all samples for observatories #39 and #40. The sandy and silty character of the fine earth is dominant, only few samples of the Luvisols have > 18 % clay. Within the sand fraction the analysed samples are fine sands derived from the schistose sandstone as the basic parent material in this area.

For the comparison of both sites some landscape characteristics have to be taken into account. The drainage lines towards the Oanob river are more strongly developed on the Duruchaus observatory. This is an effect of landscape evolution and not related to current differences in land-use. As a consequence the soils on the Duruchaus observatory are shallower in comparison to Nareis. Geomorphological depressions (pans) are restricted to Nareis and display distinct vegetation. The soils of these depressions are calcium-carbonate free, have higher silt and clay contents and are classified as Luvisols. For comparative analyses of both observatories this singular occurrence on Nareis has to be taken into account. The above mentioned differences in the development of BSCs and the vegetation composition and coverage can be regarded as a result of higher grazing impact on Duruchaus and causes visible differences.

Another, but soil chemical, difference between both areas are the topsoil pH-values which are significantly higher on the observatory #40 Duruchaus (Figure 80). From the comparison with the spectral reflectance which changes directly with land-use, also the topsoil pH-values are supposed to be a sign for different grazing intensities which might have affected the topsoils and the BSCs via trampling. However, regarding the differences in depth of the calcrete layer between both observatories, it has to be confirmed that the distribution in pH-values is not only reflecting the thickness of the rooting space above the petrocalcic horizon. The analyses revealed no correlation to the depth of such massive horizons. However, assigning this to the petrocalcic horizon is perhaps a too simple approach because a lot of nodular crust material exposed near the surface might have an influence on the pH-value. Trampling can contribute to abrasive processes on nodules contributing fine grained calcium carbonate to the topsoil.

The calcretes, the content of coarse fragments and the depth of the bedrock are assumed to be the most differentiating factors for the ecological importance for plant growth within the observatories. The depth, thickness and compactness of the calcrete are not homogenous which leads to a small scale spatial pattern of different ecological conditions which are not expressed by the classification units. A calculation of the soil volume which is available for rooting and thus for the storage of plant available water gave first insight into the complex small scale pattern of shrub or grass dominated patches. Perennial grasses are more dominant on deeper soils whereas the shallower calcretes are dominated by shrubs. Along the drainage lines and underneath the calcrete on both observatories the saprolith and paleo-soil horizons of the underlying sandstone / schist complex are found. This is an important ecological component as the calcrete is often penetrated by the roots and the saprolith provides another 30-50 cm horizon for rooting. Probably, infiltrated rainwater is even better protected against evaporation in this layer.

The genesis of the soils in and around the observatories can only be roughly described here. I assume that at first soil development and deep weathering of the schistose sandstone took place which was followed by the development of a calcic horizon within this soil. Further development into a petrocalcic horizon favours the erosion of the overlying topsoil in phases of higher morphodynamic and partly led to the dissection of the calcretes. Today, the soils are still vulnerable to water erosion during heavy rain events although the biological soil crusts have a stabilising effect.

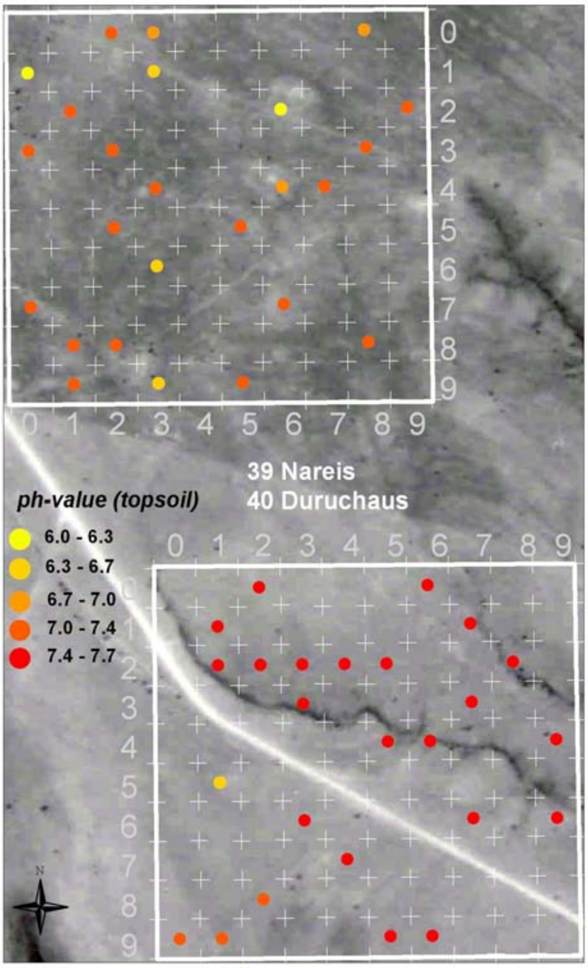


Figure 80 Distribution of topsoil pH-values on the observatories #39 and #40

3.7 Observatories 10 (Gellap Ost) and 11 (Nabaos)

3.7.1 Regional overview

This chapter describes a pair of observatories in the arid Nama Karoo, established in direct vicinity of each other with a marked fence line contrast between both. The area belongs to the Karas Region and is situated approx. 15 km northwest of Keetmanshoop. One observatory is located on the Gellap Ost Research Station which has a total area of 13.734 hectares. The 2nd observatory is situated in the Tiervlei, a part of a large communal area towards the north.

The average rainfall of around 150 mm is precipitating during the summer months with a major share from December to February. However, the rainfall has a pronounced variability which is around 70 % to 80 % for this southern area of Namibia (MENDELSOHN et al. 2002). Mean annual temperature is approximately 20-22 °C. With regard to vegetation types, the region belongs to the Karas Dwarf Shrubland characterised by grasslands, low shrubs and only few trees.

Geologically, the region belongs to the Karoo Supergroup characterised by the Main Karoo Basin group with sedimentary shales and schists and the intruded Keetmanshoop Dolerite Complex with landscape characterising dykes and sills (for details see GENIS & SCHALK 1984, GERSCHÜTZ 1997, SCHNEIDER 2004). The sediments into which the dykes and sills intruded are part of the Dwyka and Ecca groups of the Karoo Sequence. These softer sediments were eroded more easily than the harder dolerites which usually cap hills or plateaus in the area today.

The topography of the area is dominated by large plains and slightly inclinated washes or glacis structures towards the riviers. Prominent features are dolerite hills and dykes as well as ‘inselbergs’ of the shale which typically have a cone-like shape. Partly, harder layers within these shales build up small plateau covers.

Most important land-use in the region is sheep and goat farming in fenced camp systems or open access systems as in the Tiervlei communal area (KUIPER & MEADOWS 2002). The most important pressure on the environment is overgrazing leading to a reduction in plant cover and / or a shift in the natural vegetation. Reduced plant cover enhances soil erosion which is present in the form of water and wind erosion in the area.

3.7.2 Observatory description

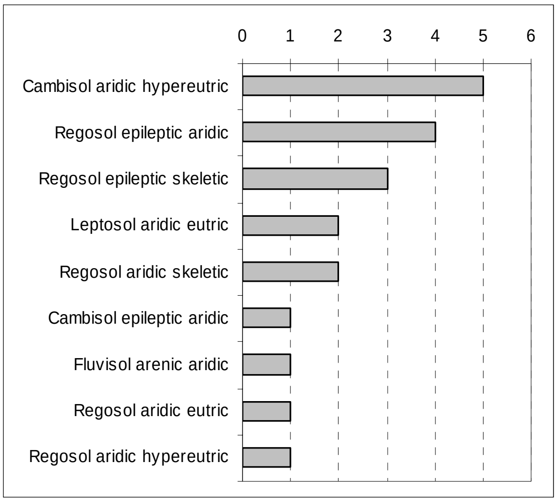
The observatories #10 (Gellap Ost) and #11 (Nabaos) are situated close to each other separated by the fence of the Gellap Ost Research Station. Both observatories are dominated by a glacis structure with a slight inclination of 4-5 % towards the west. The mean height is approx. 1100 m asl. Some shale outcrops occur within the observatories while dolerite is not present in this area. In order to compare the two observatories is has to be considered that Nabaos is influenced by a larger catchment in the eastern surrounding which causes a stronger drainage structure in the observatory.

In Gellap Ost the dominant vegetation types are grassland or dwarf-shrub savanna with the main species *Boscia foetida*, *Catophractes alexandri*, *Leucosphaera bainesii*, *Phaeoptilum spinosum*, *Rhigozum trichotomum* and perennial grasses like *Stipagrostis hochstetteriana* and *Stipagrostis uniplumis*. Larger trees like *Acacia erioloba* are restricted to the rivier structure. The observatory Nabaos is characterised by degraded shrubland and significant signs of soil erosion. The grazing history of this place dates back to the early seventies, when the ownership changed from commercial to communal tenure (Odendaal plan, see KUIPER & MEADOWS 2002). Compared to Gellap-Ost, the vegetation of the plains is lower and dominated by shrubs like *Acacia* spp., *Calicorema capitata*, *Rhigozum trichotomum*, *Tetragonia schenckii* and *Salsola* spp. and more ephemeral grasses like *Aristida adscensionis* and *Schmidtia kalahariensis* (www.biota-africa.org). The habitats of both observatories were assigned by topography into the units i) plain, ii) slope/outcrop and iii) rivier.

3.7.3 Soils

3.7.3.1 Main soil units

On each observatory 20 locations were investigated and sampled. According to the WRB (1998) the reference groups Cambisol, Leptosol, Regosol and Fluvisol are found. As depicted in Figure 81, Cambisols and Regosols are the most dominant soil units, which together account for 85 % of the studied profiles. The predominance of the Regosols (50 – 55 %) is a sign for the low importance of soil forming processes in the study area.



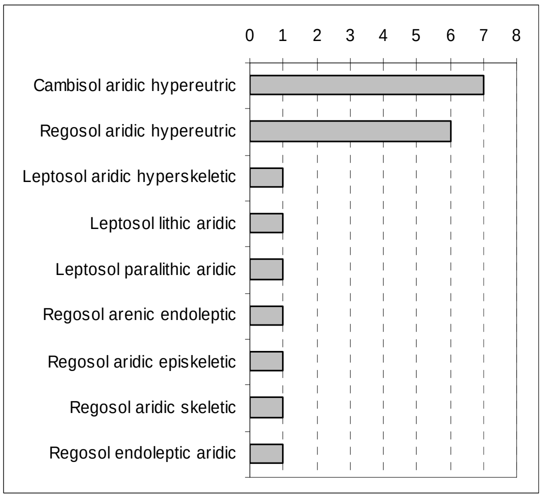


Figure 81 Frequency distribution of WRB (1998, 2nd qualifier level) soil units in the observatories #10 (Gellap Ost, left) and #11 (Nabaos)

The different soil units of the observatories and their distribution are shown in Figure 82. The most important driving factors for the soil properties and the classification are the type and age of substrate, the depth of the profiles and the content of coarse fragments. The observatories cover plains and washes with shale outcrops of the Karoo Sequence (Ecca Group, Prince Albert Formation after GENIS & SCHALK 1984). The soil parent materials are shale (partly shattered and with thin calcareous layers) and colluvial materials (sand to loam) of different ages.

The rocky outcrops and slopes are dominated by shallow Leptosols and Epileptic Regosols whereas the plains and washes are characterised by weakly developed Regosols. Partly stronger developed Cambisols occur on ridges with loamy parent material in the plains. At the basis and footslopes of the outcrops also in situ developed Cambisols were found. These Cambisols are associated with Epileptic Regosols. A unique Fluvisol is situated in the southwest corner of the Gellap Ost observatory in the broad rivier structure.

A typical catena from an outcrop in the east to the rivier in the west would show the following sequence: Leptosols > in situ developed epileptic Regosols > in situ developed Cambisols > deep Regosols and Cambisols > Fluvisol.

A common feature of all soil units is the development of a 'desert pavement' on the soil surface which consists of fine to coarse gravel. This indicates a continuous influence of wind erosion of the silty substrates. In the loamier substrates often an additional vesicular layer is found in the first centimetre of the topsoil. These features in many cases led to the use of the qualifier aridic.

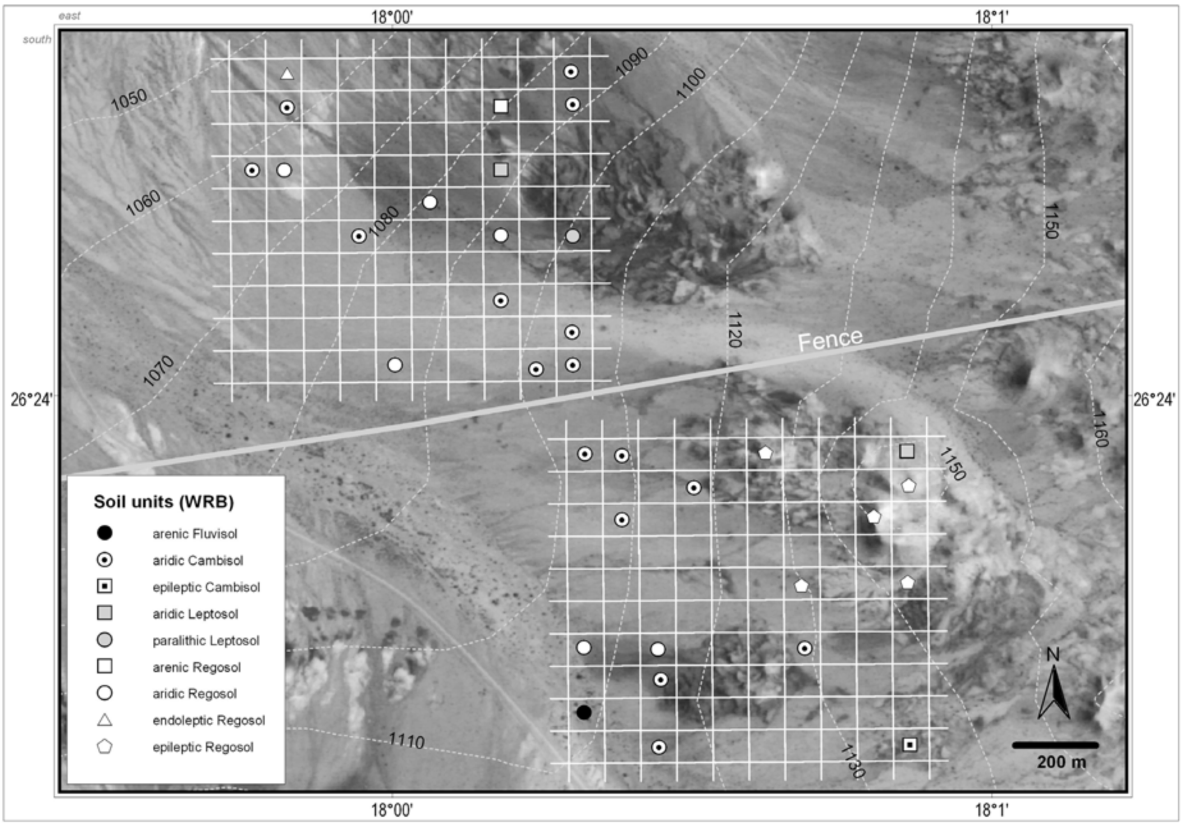


Figure 82 Distribution of soil units (WRB 1998, 1st qualifier level) on the obs. #10 and #11

3.7.3.2 Remarks on classification

The most important features and the differences of the soils (cambic horizons, content of coarse fragments, depth of bedrock) could be described adequately with the provided qualifiers and reference units of the WRB (1998) classification system. The possibilities for the separation of soil physical properties are very detailed in the Regosols by applying the prefixes ‘epi’ and ‘endo’ additionally. This leads to a very detailed naming of the soil units (by physical properties) and gives the impression of high soil diversity compared to other regions. In fact, the chemical soil properties do not vary as strongly.

The classification of the Leptosols and the Fluvisol is explicit due to the depth of the bedrock and the fluvic requirements whereas the classification of the Cambisols and Regosols allows some room for interpretation. Cambisols in the slope or footslope positions often show clear features of in situ soil development in form of residual bedrock structure and a continuous weathering zone into the bedrock. The loamier soils within the plains also fulfil the requirements of cambic horizons but it cannot be excluded that these substrates are of colluvial genesis and no further in situ development was evident. The Regosols in the plains often show signs of stratification which indicates a colluvial genesis. These signs are not evident in the Cambisols, thus I decided to separate the plain soils into these two classes, the Cambisols as the browner, loamier soil unit with a more homogenous structure and probably a longer soil genesis, and the Regosols with sign of stratification, a sandier texture and a more greyish colour.

The application of the new version of the WRB (2006) reveals only minor changes. The new introduced qualifiers 'siltic' and 'clayic' now allow expressing the higher clay and silt components in some Cambisols and Regosols. For the qualifiers aridic and arenic the ranking changed to a lower priority.

3.7.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **67**	Ha: **09** Obs: **10**	Classification (WRB 1998) **Eutri - Aridic Leptosol** (WRB 2006) **Haplic Leptosol (Eutric, Aridic)**

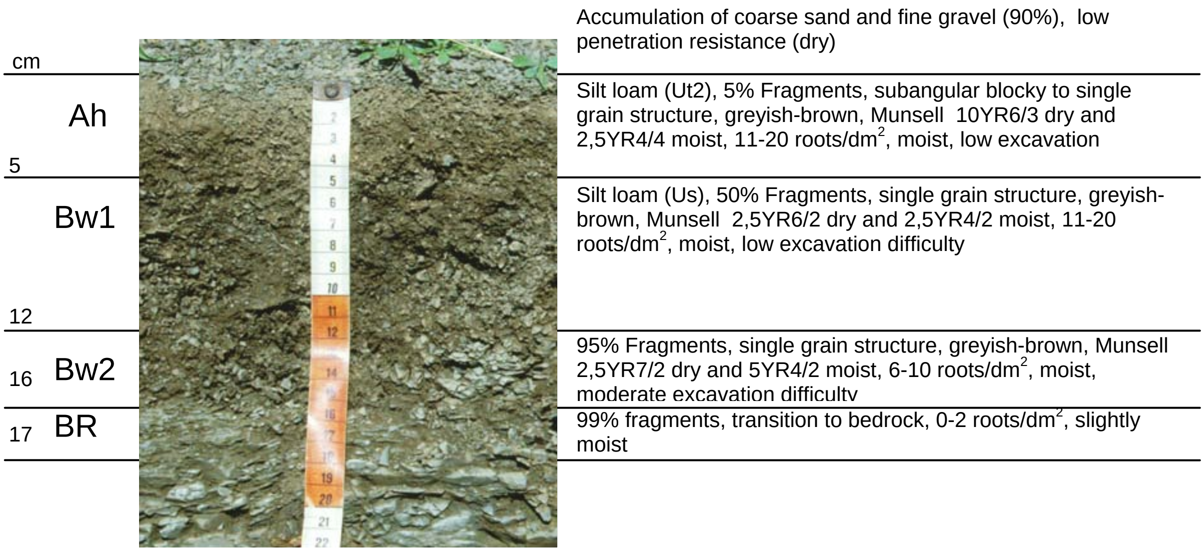


Figure 83 Description of profile 67

The Eutri-Aridic Leptosol of Figure 83 is typical for shallow soils developed in the shale derived substrates of the rocky outcrops and their surrounding slopes. Typically the bedrock starts within 25 cm below the soil surface and the substrates have a high content of coarse fragments. The soil surface and the first horizon have a loose structure though the bulk density proved to be relatively high (1.6 g cm^{-3}).

The texture of the fine earth is dominated by silt and sand and has some specific properties which are the result of shale as soil parent material. The physical weathering led to a variety of grain sizes which all consist of the same material. This is different to other soils where often sand fractions consist of quartzes or other weathering resistant minerals. Moreover, the particles have a relatively low resistance against pressure which causes a continuous breakdown of material when pounding for the finger test. The resulting texture therefore ranges from silty sand to silt, depending on the kind of texture analyses. As the sand size particles and also coarser gravel are porous and thus able to store water it is recommend to be careful with texture derived interpretation of the water supply in this substrates.

Soil reaction is slightly to moderately acid and the organic carbon reaches only 0.1 % in the fine earth which is not atypical for an arid environment. However, one has to be cautious with the interpretation of the organic carbon content as the shale already bears considerable amounts of organic carbon and especially nitrogen. The enlarged nitrogen contents lead to very low C/N ratios between 1 and 4 (see discussion below. The electrical conductivity (EC) is very low with 10-15 µS cm^{-1} across the entire profile.

Total element contents and TRB show no significant changes with profile depth. The content of water soluble ions is very low with 3-5 $mmol_c\ kg^{-1}$. The CEC (not shown in the Fig.) is 110 $mmol_c\ kg^{-1}$ in the topsoil and 60 $mmol_c\ kg^{-1}$ in the second horizon which has lower silt and clay contents.

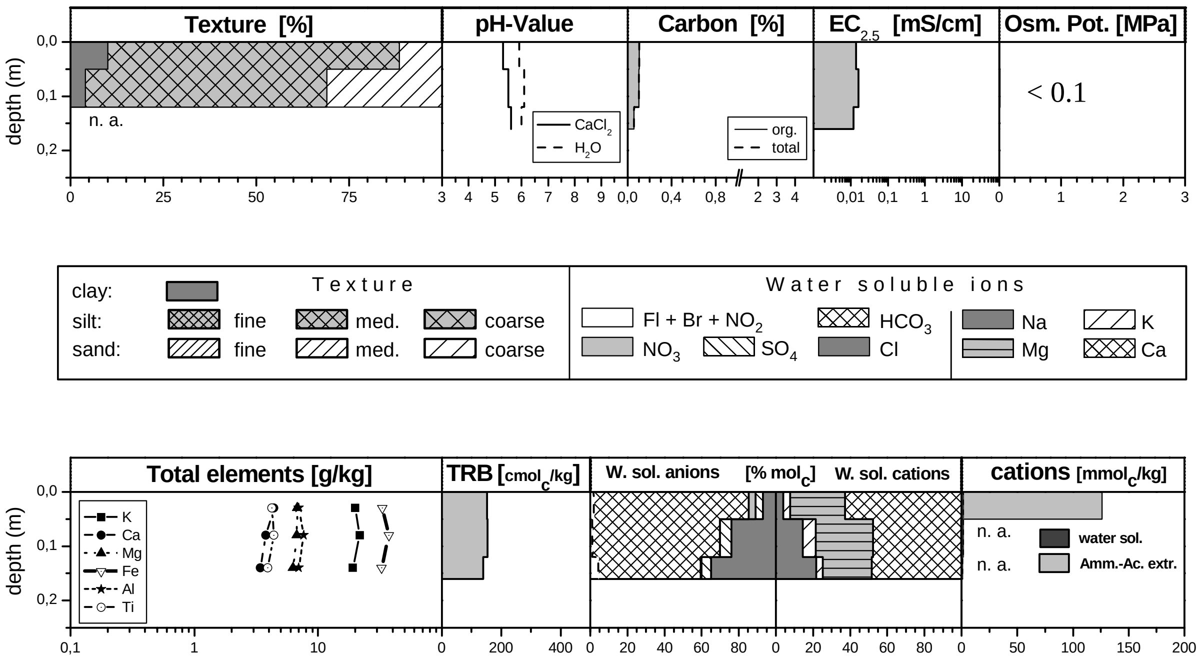


Figure 84 Properties of profile 67

Reference profile # 2

Profile: **71**	Ha: **99**	Classification (WRB 1998)	**Aridi-Epileptic Cambisol (Episkeletic Hypereutric)**
	Obs **10**	(WRB 2006)	**Epileptic Cambisol (Hypereutric, Episkeletic, Aridic, Clayic)**

Depth (cm)	Horizon	Description
		Accumulation of coarse sand and fine gravel (80%) low penetration resistance (dry)
0–10	Ah	Sandy loam (Sl3) with coarse sand (gSms), 20% fragments, single grain structure, brownish-dark grey, Munsell 2,5YR5/2 dry and 5YR3/2 moist, 6-10 roots/dm^2, moist, low excavation difficulty
10–30	Bw1	Clay loam (Lt2) with coarse sand (gSms), 50% fragments, subangular blocky to massive structure, (greyish-)brown, Munsell 10YR6/2 dry and 2,5YR4/4 moist, 3-5 roots/dm^2, moist, moderate excavation difficulty
30–42	Bw2	Clay loam (Lts) with coarse sand (gSms), 50% fragments, subangular blocky to massive structure, (greyish-)brown, Munsell 2,5YR6/2 dry and 2,5YR4/4 moist, 3-5 roots/dm^2, moist, moderate excavation difficulty
42–46	BR	Transition to bedrock, Clay (Tl), 90% fragments, grey, Munsell 5YR4/2 dry and 5YR3/2 moist, moist

Figure 85 Description of profile 71

The Aridi - Epileptic Cambisol of Figure 85 is a typical example for soil with some in situ development and with contact to the shale bedrock. Additionally, in this example a colluvial modification is clearly detectable in the topsoil. These mass transport derived horizons are found in many profiles in the observatories and indicate phases of strong morphodynamic processes followed by a phase of more stable and moister conditions in which the in situ weathering occurred and thus the Cambisol developed.

The colluvial topsoil horizon consist of sandy loam, the typical texture for the youngest sediments which forms thin layers on older surfaces or in the case of the Regosols thick layers dominating the soil properties (see reference profile 3). The texture of the browner subsoil horizons is clay loam with a high content of coarse fragments (shale).

Soil reaction is slightly to moderately acid and the organic carbon reaches 0.4 % in the fine earth. The high initial content of organic carbon in the shale can be detected by the increase in the horizon above the bedrock where many fine grained, fresh shale particles are in the sample. Mean C/N ratio is 2 and the EC is low with 20 -70 µS cm^{-1}.

Despite the very different textures and colours of the horizons the total element contents and the TRB show no significant changes with profile depth. This is an indication for the homogeneity of the parent material which obviously is not strongly affected in its geochemical composition by different states of weathering. Pedogenic iron (indicated by Fe_d/Fe_t) only shows slight differences with 25 % in the colluvial horizon and 30 % in the subsoil.

The content of water soluble ions is very low with 3-5 $mmol_c\ kg^{-1}$. The CEC (not shown in the Fig.) is 90 $mmol_c\ kg^{-1}$ in the topsoil and 160 $mmol_c\ kg^{-1}$ in the subsoil.

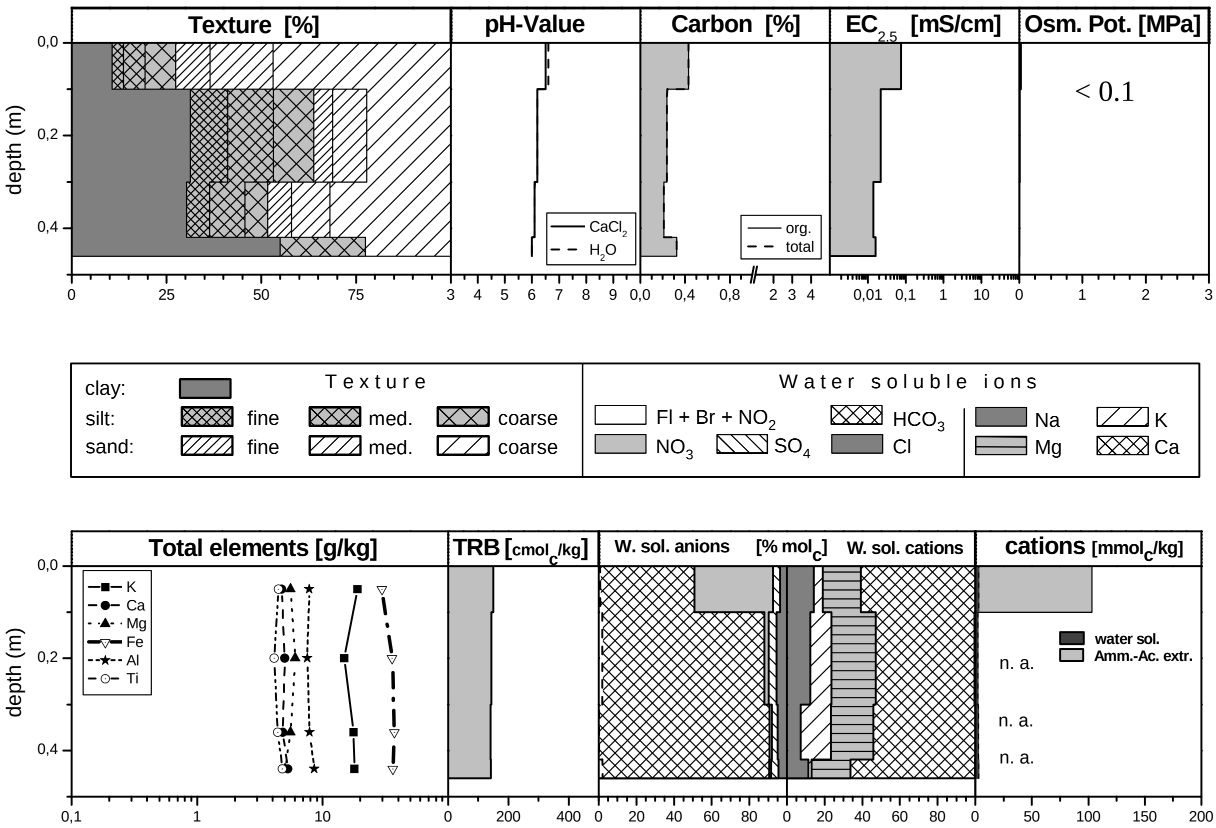
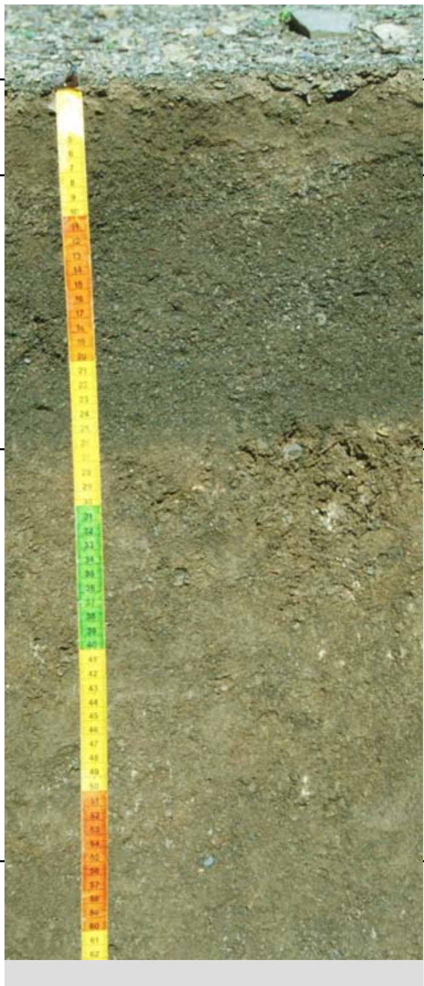


Figure 86 Properties of profile 71

Reference profile # 3

Profile: **85**	Ha: **31** Obs: **11**	Classification (WRB 1998) (WRB 2006)	**Hypereutri - Aridic Regosol** **Haplic Regosol (Hypereutric, Aridic)**



cm	Horizon	Description
		Accumulation of coarse sand and fine gravel (80%) low penetration resistance (dry)
0–6	Ah	Sandy Loam (Sl3) with coarse sand (gSms), 10% fragments, single grain structure, brownish-grey, Munsell 2,5YR6/2 dry and 2,5YR4/2 moist, 3-5 roots/dm^2, dry, low excavation difficulty
6–26	Bw1	Sandy Loam (Sl3) with medium sand (mSgs), 10% fragments, single grain structure, brownish-grey, Munsell 2,5YR6/2 dry and 2,5YR4/2 moist, 3-5 roots/dm^2, slightly moist, low excavation difficulty
26–55	Bw2	Sandy Loam (Sl2) with fine sand (fSms), 10% fragments, subangular blocky structure, moderately calcareous, greyish-brown, Munsell 10YR7/3 dry and 2,5YR4/4 moist, 1-2 roots/dm^2, moist, moderate excavation difficulty
55–100	Bw3	Sandy Loam (Sl3) with coarse sand (gSms), 10% fragments, single grain to subangular blocky structure, moderately calcareous, greyish-brown, Munsell 2,5YR6/2 dry and 2,5YR4/4 moist, moist, moderate excavation difficulty

Figure 87 Description of profile 85

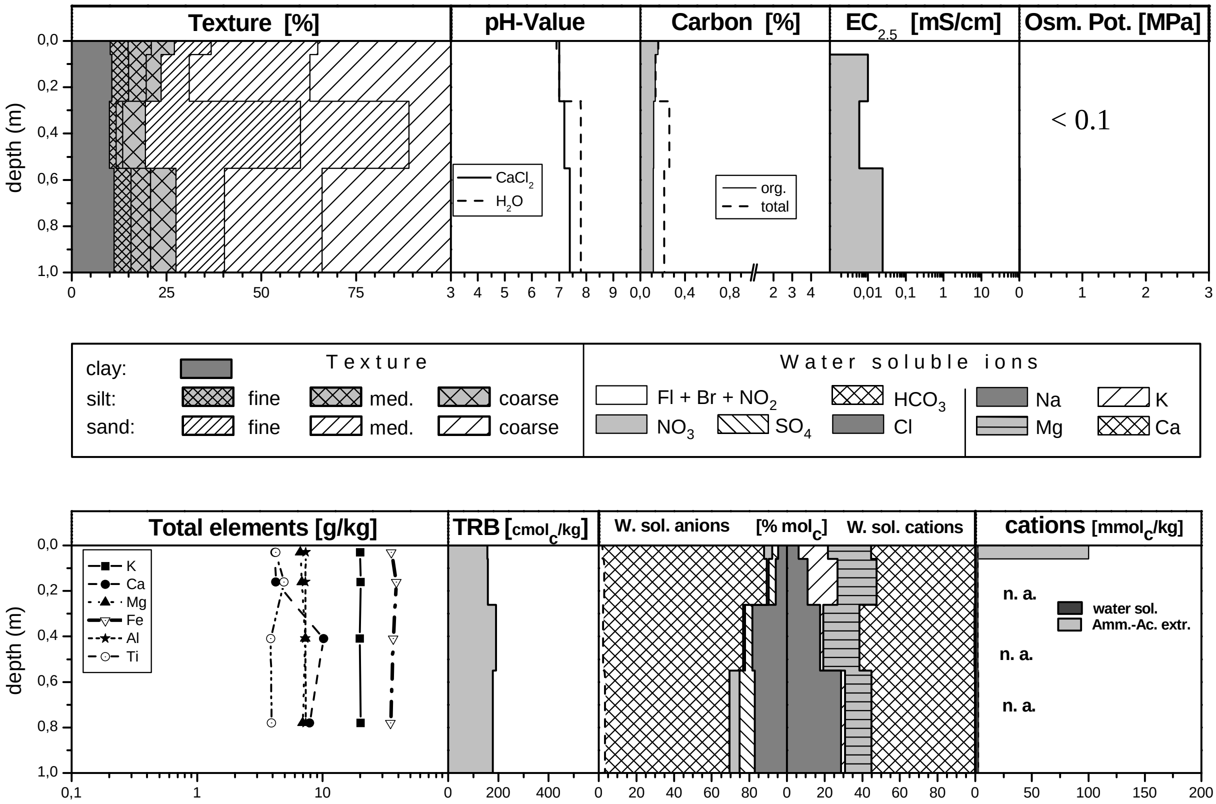


Figure 88 Properties of profile 85

The Hypereutri-Aridic Regosol of Figure 87 represents the soils of the plains with more sandy and younger colluvial substrates. These soils are associated with deep developed Cambisols on loamier ridges which are also most likely of colluvial genesis.

This profile shows signs of stratification as a result of strong morphodynamic processes with massive substrate transport. From the profile morphology it can be concluded that at least three sedimentation events led to the actual substrate stratification (Ah, Bw1, Bw2-Bw3).

All horizons consist of sandy loam, the typical texture for the young colluvial sediments. The strong reduction of the coarse sand fraction in the Bw2 horizon even implicates a fourth substrate stratum which was not indicated by the profile morphology

Soil reaction is neutral to slightly alkaline and the organic carbon reaches 0.2 % in the fine earth of the entire profile. In the horizon below 26 cm a slight accumulation of calcium carbonate is evident. Mean C/N ratio is 1.3 and the EC is very low in the entire profile.

Except for the increase of calcium the total element contents and TRB show no significant changes with profile depth. This is an indication for the homogeneity of the parent material. The content of water soluble ions is very low with 3 $mmol_c\ kg^{-1}$. The CEC (not shown in the Fig.) is 70 $mmol_c\ kg^{-1}$ in the topsoil and 90 $mmol_c\ kg^{-1}$ in the subsoil. The content of pedogenic iron is around 25 %.

3.7.3.4 Discussion of soil properties

In these observatories the variability of soil properties is defined by soil physical properties, mainly texture and the available rooting space, i.e. content of coarse fragments and depth to bedrock. For all other parameters shown in Figure 89 the variability is low to moderate. Remarkably low is the vertical difference in the profiles. In the case of organic carbon this is due to the dominance of background carbon contents in the parent material which overrides the organic carbon contents by in situ humus accumulation.

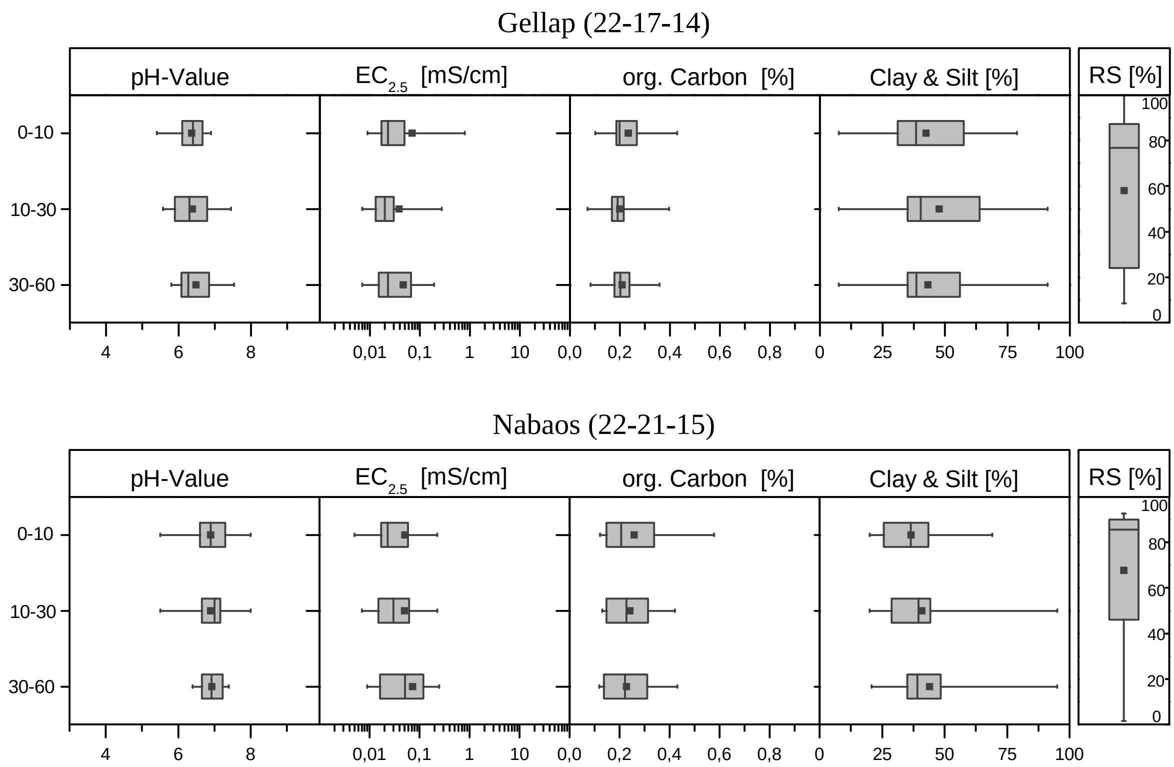


Figure 89 Variability of selected soil properties in three depth intervals for the observatories #10 and #11

Box =25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS= rooting space

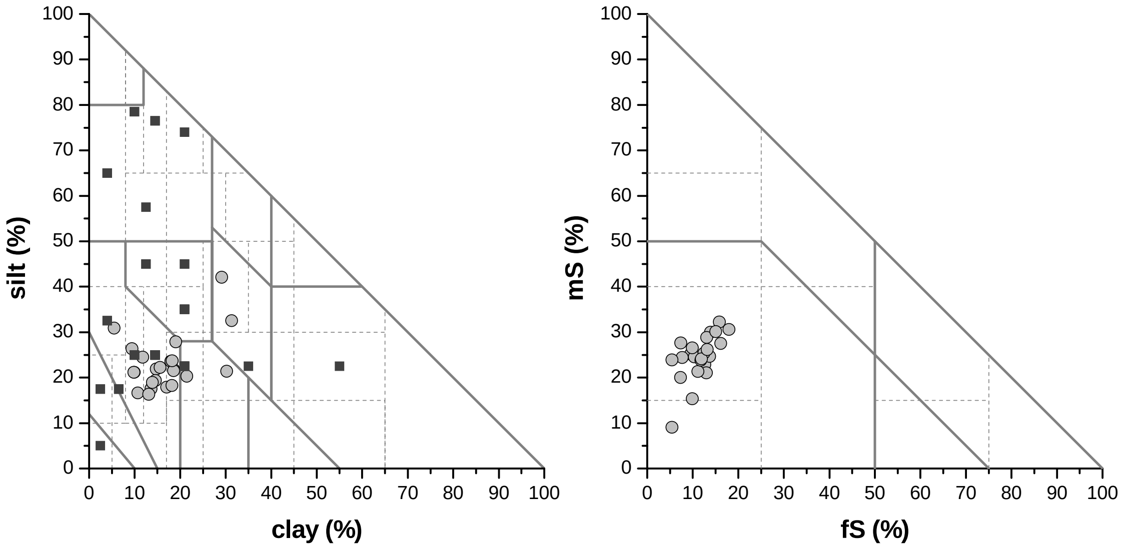


Figure 90 Results of the texture analyses for the observatories #10 and #11
Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 90 reports the results of the texture analyses. The sandy and silty character is prominent, only few samples of the Cambisols have more than 30 % clay in the fine earth (finger tests). Within the sand fraction the analysed samples can be described as coarse sands (gSms).

Further typical features of the soils are the relatively low EC, high carbon and nitrogen contents of the parent material and the lack of microbiotic crusts. The low EC indicates a regular deep drainage of the soils which does not allow the accumulation of soluble salts. The trend of higher EC values in loamier textures strengthens this theory as these textures are not drained as intensively as the sandy ones. Accumulation of transported soluble salts are visible in the northwestern part of Nabaos where thin salts crust occur at the transition from the loamier ridges to the drainage lines. The relatively high contents of organic carbon (up to 0.8 %) and nitrogen (up to 0.15 %) of the shale lead to untypical C:N ratios between 1 and 4 in the soils but the nitrogen seems to be relatively stable in the parent material. Nitrate concentrations in the soils are relatively low. Due to this geogenic background the organic carbon is not useable as an indicator for the degradation comparison between both observatories. A further 'atypical' feature is the dark grey colour of the shale that will raise soil temperature significantly under high radiation compared to lighter substrates. Higher temperatures might also be an advantage in the formation of vesicular layers which are most likely a result of water vapour creating the micro-bubbles in wet topsoil (VOLK & GEYER 1970, MILLER 1971).

The spectra of occurring soil units in both biodiversity observatories are comparable, indicating a similar abiotic environment for vegetation and animal life. Slight differences in the soil properties may be due to small-scale variations in soil parent material and differences in the size of the catchment areas which influences the relevance of run-off events and sediment transport processes on the study sites. The trend of higher pH-values in Nabaos is probably a result of a higher proportion of thin calcareous layers in the parent material.

I assume that the texture, the content of coarse fragments and the depth of the bedrock are the most differentiating ecological factors for plant growth conditions as they drive the water supply. On Gellap Ost a clear trend of denser grass cover on the sandier soils than on the neighbouring loamy ridges is visible. The restriction of water supply on the loamier soils is caused by stronger physical crusting effects which reduces the infiltration and enhance run-off, and by higher evaporation losses due to stronger capillary rise. The run-off run-on situations combined with different depth of soils and bedrock situations lead to a small scale distribution of rainwater. Besides the pattern of loamy and sandy sites also clear linear structures of bushes and trees along the drainage lines indicate the higher water supply by surface run-on.

This basic pattern is hardly visible in Nabaos where permanent heavy grazing has led to a deterioration of grass cover and heavy trampling has led to a visible increase in soil disturbances. In the long run, the reduced plant cover will result in continuous loss of soil due to erosion, also affecting the soil seed banks which are important for the natural regeneration capacity of the vegetation. A second alarming indicator for soil degradation might be the stronger development of vesicular layers in the topsoil which also reduces infiltration. Higher temperatures in the topsoil due to reduced plant cover probably support the development of these layers which are common in this region.

The genesis of the soils in and around the observatories can only be roughly described here and is rather speculative. The existence of red-brown, clay-rich saprolitic material in pockets between the bedrock outcrops indicates the oldest form of soil formation. These soils are nearly completely eroded today.

I assume an initial soil development under moister conditions when most of the Cambisols material developed. This phase must have been followed by massive transports of soil materials. Most likely the loamy parent material in the plains is a result of this process. This phase was followed by a more arid climate with physical weathering as the dominant process and subsequently mass transports which again translocate soil material into the plains where it covers to some extent the loamy phases. These mass transports and erosion processes are still the most important soil forming processes to date. Today, soils are still vulnerable to water and wind erosion. Therefore the reduction of plant cover by overgrazing but also by natural droughts strongly enhances the erosion risk.

3.8 Observatory 16 Wlotzkasbaken

3.8.1 Regional overview

The observatory #16 (Wlotzkasbaken) is located in the coastal plains of the central Namib desert approx. 40 km north of the town Swakopmund in the Erongo Region (see Figure 91). This part of the desert is a gravel plain without dunes, traversed by numerous dry washes and small riverbeds. The homogeneous terrain is interrupted by a few inselbergs only and rocky ridges running in a SW-NE direction. The Namib is one of the driest places in the world, especially the coastal peneplains which are strongly influenced by the climatic effects of the Benguela current. Mean annual rainfall is only 10 mm with nearly 100 % variation resulting in periods of several years without any rainfall at all. Only few thunderstorms from the escarpment reach the outer parts of the Namib. Mean annual temperature is around 16-18 °C, increasing with the coastal distance. Air temperatures as well as humidity are strongly affected by fog. Fog occurs on 75-100 days per year and is assumed the most important source of moisture for various groups of organisms, especially for the typical lichen and biological soil crust communities (SCHULTZ 2006). Measurements indicate an input of 34 mm/a near the town Swakopmund (GOUDIE 2002). However, the majority of moisture evaporates directly in the afternoon hours when the southwesterly winds and the strong insolation dissolve the fog. Two main wind directions are typical for the Central Namib region. The SW-winds, as a see-land wind, dominate the summer months during the day. In winter, periodical strong hot and dry NE-E-winds are characteristic. These easterly winds bring high temperatures caused by the adiabatic temperature rise of the upland plateau air masses and transport huge amounts of sediments that partially have strong abrasive effects through the sand fraction near the ground and transport the finer silt into the sea.

The natural vegetation is characterised by lichen communities, dominated by the shrubby *Teloschistis capensis* responsible for the colourful aspect of the plains. Only some higher plant species such as *Arthraerua leubnitziae, Psilocaulon subnodosum* and *Zygophyllum simplex* occur sparsely and are concentrated along drainage lines (HACHFELD & JÜRGENS 2000).

Geologically, the region is situated in a zone dominated by the Swakop group of the Damara sequence with intrusive and metamorphic sedimentary rocks with granites and schists in changing proportions. These bedrocks are cut by individual dolerite dykes of ten centimetres to several tens of meters width, regularly extending for many kilometres. Due to their resistance to weathering, the larger dolerite dykes tend to form prominent dark ridges in the landscape and are important microhabitats. The larger ones also prevent lichen fields from abrasion by sand storms during east winds.

The topography of the area is almost flat to gently undulated with an increasing steady rise in height by 1 – 2 % in an easterly direction from the sea level to 1000 m asl 100 km inland.

Major landforms are plains and in smaller portions riviers, dolerite ridges and few rocky outcrops.

There is no agricultural land-use in the area. However, the main threat for this natural environment is the recreational activity of tourists and others, which often use the landscape for off-road driving with 4x4 vehicles and quadbikes. The highly sensitive lichen fields and biological soil crusts cannot withstand these pressures and the signs of tracks thus remain carved into the landscape for decades. At the same time, the lichen fields are one of the main attractions and world famous for their unique aspects and ecological system.

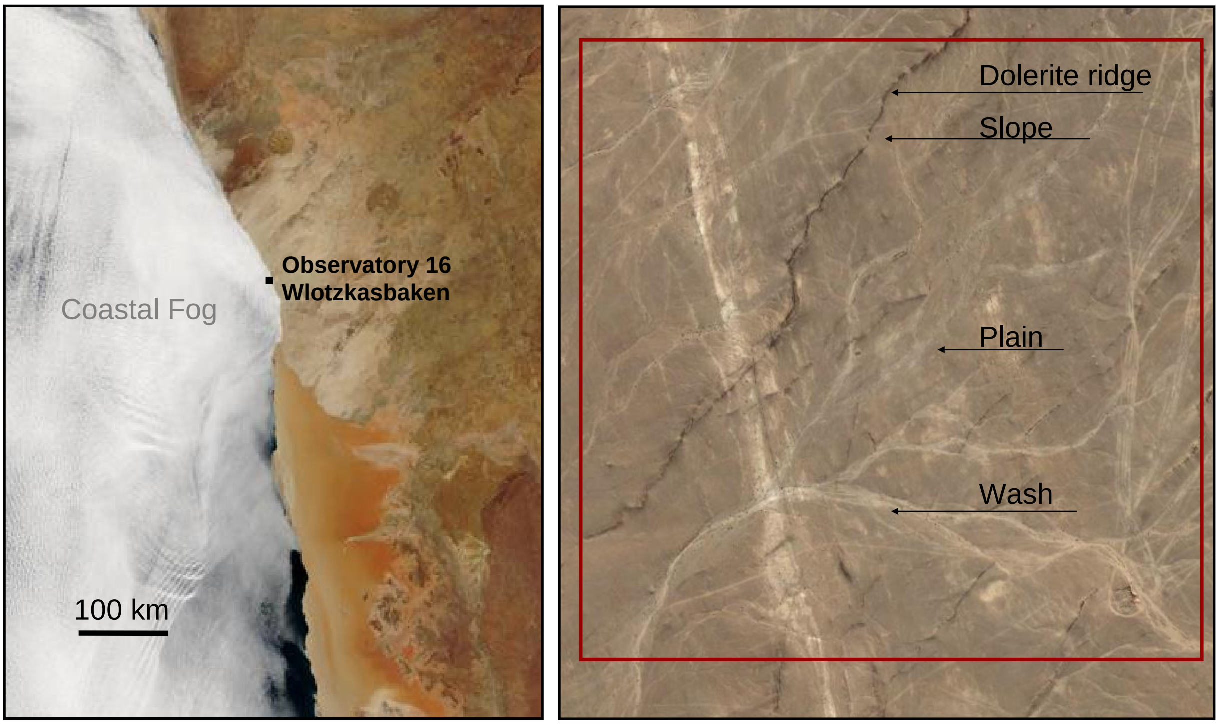


Figure 91 Left) Satellite view (MODIS) of the Namib desert with fog banks along the coast and the sandsea south of the Kuiseb river Right) Satellite view of the observatory #16 Wlotzkasbaken with main habitat types (Google Earth)

3.8.2 Observatory description

The observatory itself is situated approx. 10 km north of the small periodical tourist settlement of Wlotzkasbaken with a coastal distance of 5 km. The topography is flat with heights of 64 – 84 m asl and a slight inclination towards the west. One larger (10 m width) and several smaller dolerite dykes are stretching through the observatory in typical NE-SW direction. These ridges are only slightly higher than the surrounding plains and washes. Other substrates include unconsolidated materials with a maximum depth of 50 cm, overlying schists and granites. A unique feature is a band of white, coarse-grained calcite marble from the Karibib formation that cuts through the observatory in NNW-SSE direction. It is almost exposed to the surface. The unconsolidated substrates consist mainly of gravel and sand covered by a desert pavement of medium sized quartz pebbles covering 60-100 % of the soil surface. The typical aspect of the lichen-dominated vegetation is shown in Figure 92. Resulting from the abrasive processes through strong east winds, the east exposed sides of larger dolerite boulders are free of lichen colonisation.

Figure 92 Left) Typical aspect of the lichen field in the observatory Wlotzkasbaken with a stand of *Teloschistes capensis* Right) Abrasive processes result in lichen free ventifacts on east exposed sides

The observatory is dissected by small and shallow drainage lines, which indicate surface drainage during the rare intense rainfall events. Due to the importance of small-scale topography, seven habitat types were chosen as plain, wash, dolerite ridge, slope and transition types between these four main features. The habitats are shown exemplary in Figure 91.

One typical feature of the coastal plain, as well as of the observatory, is the soil enrichment with gypsum in form of powder, concretions or massive crusts. According to GOUDIE (2002), the formation of gypsum is caused by biogenic sulphur compounds provided by hydrogen sulphide eruptions from the Benguela sediments along the coast of the Atlantic Ocean. Contrary to previous assumptions, the regular fog events do not contribute to the input of sulphur, as precipitated water is almost sterile. It is assumed that rather single events (‘blow outs’) than frequent input are the main source of sulphur precipitating with fog in short periods of time. The necessary calcium for the precipitation of gypsum is provided by calcite bedrocks and a lot of calcretes material.

3.8.3 Soils

3.8.3.1 Main soil units

20 soil profiles were examined according to the standardised procedure. The soil units of the observatory #16 (Wlotzkasbaken) and their distribution are provided in Figure 93.

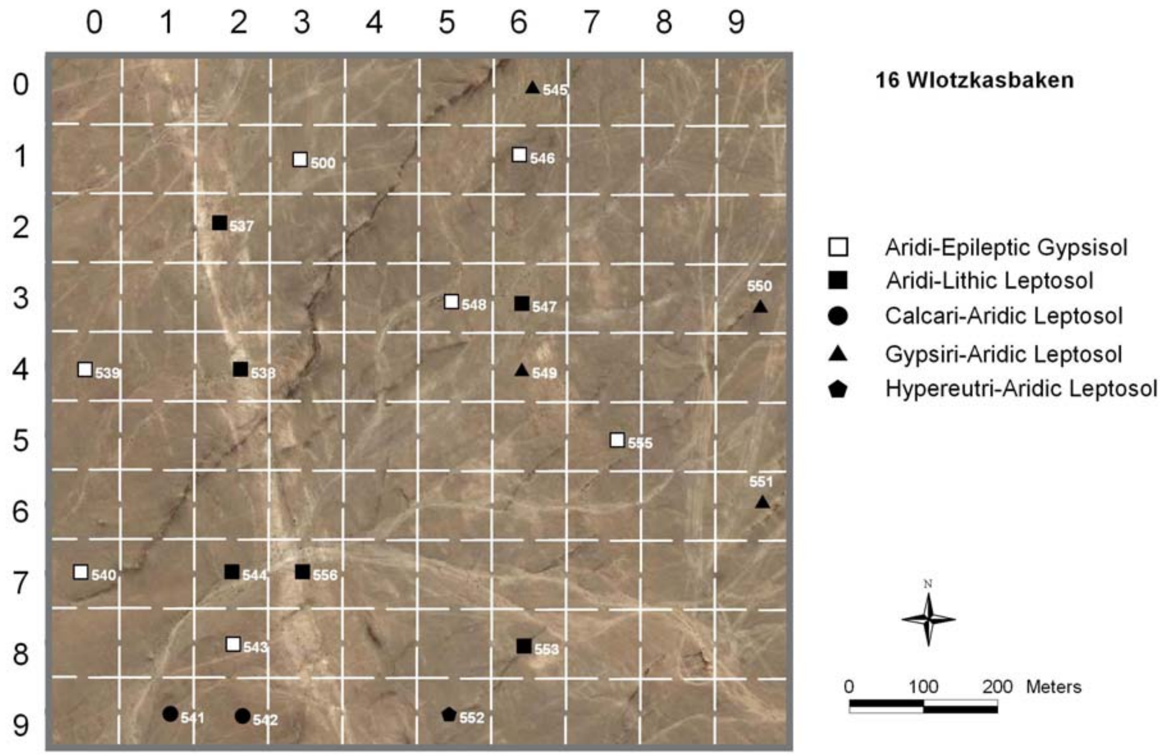


Figure 93 Distribution of soil units (WRB 1998, 2nd qualifier level) on #16 Wlotzkasbaken

According to the WRB (1998), the reference groups Gypsisol and Leptosol are found; in Figure 94 the frequency of these soil units is displayed. Approximately one third of the profiles are Gypsisols, which are predominantly found in the plain habitat and characterise the sites with high gypsum content. However, these soils are shallow, as expressed by the qualifier ‘epileptic’. Profiles with shallower bedrock and lower gypsum contents classify as Leptosols, partly ‘calcaric’ and ‘gypsiric’. In some places, especially on the calcite marble, only very shallow soils or substrate layers cover the bedrock. This is marked by the qualifier ‘lithic’. A common feature of nearly all profiles is the combination of a desert pavement with ventifacts overlying a thin silty layer, low OC values and alkaline topsoil conditions marked by the qualifier ‘aridic’.

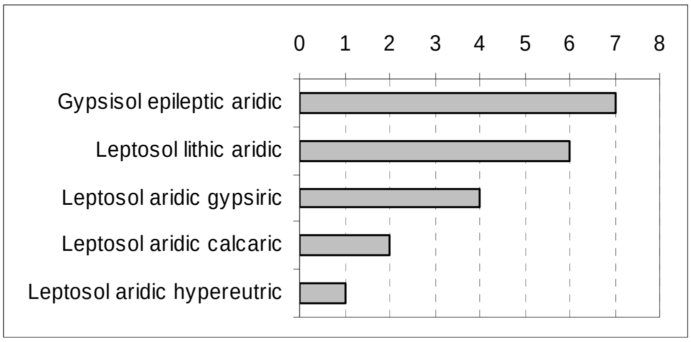


Figure 94 Frequency distribution of WRB soil units in observatory #16 (Wlotzkasbaken)

3.8.3.2 Remarks on classification

The classification of the soil units is provided in the WRB (1998) nomenclature. The most important features and differences of these soils (depth, gypsum and calcium carbonate content, high pH and desert pavement) could be described sufficiently with the provided qualifiers and reference groups. However, the degree of salinity is not describable with the WRB, although this is also an important feature.

The application of the new version of the WRB (2006) reveals major changes. The newly introduced definitions for the salic horizon now allow expressing the salinity by the choice of Solonchaks. For the shallower soils, it can be marked with the qualifier ‘salic’ which is now also applicable in the Leptosols. A further development is the qualifier ‘nudilithic’ which separates exposed bedrock from very shallow Leptosols. The profiles on marble fulfil this requirement. Another important change is the reduction of the amount of gypsum for the gypsic horizon from 15 % to 5 %. Several additional profiles will now be in the reference group Gypsisols. In summary, the new version enables a more precise description of the main soil features in this observatory and emphasises its salty properties.

3.8.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **540**	Ha: **70**	Classification (WRB 1998)	**Aridi - Epileptic Gypsisol**
		(WRB 2006)	**Gypsic Hypersalic Solonchak (Aridic)**

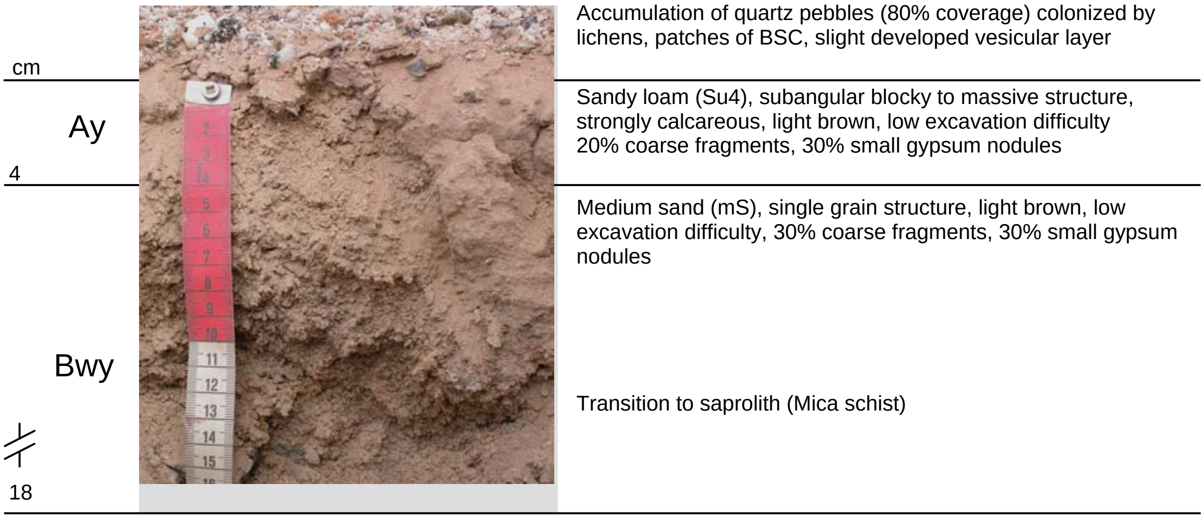


Figure 95 Description of profile 540

The Aridi-Epileptic Gypsisol of Figure 95 is a typical example for the soils of this observatory, which are developed in a thin weathered zone of the underlying schist and granites. Due to the similarities to other profiles, it is selected as the only reference profile. The main texture of the Bwy horizon is a medium sand with small amounts of silt. The Bwy horizon clearly derives from the schist. The thin Ay is the typical silt rich topsoil with desert pavement and a slightly cemented structure. This layer also shows higher values in organic and inorganic carbon. The EC is relatively high for sandy substrates resulting in high osmotic potential of 1-2 MPa (calculated). However, the fact that the $EC_{2.5}$ does not exceed 2 mS cm^{-1} and that the quotient of $EC_{2.5}$ / EC_5 is 1.2 indicates the dominance of gypsum (see methods for explanation). Consequently, the osmotic potential would not reach such high values as calculated because the solubility of gypsum is relatively low. The moderately alkaline pH-value is constant over depth whereas the total element content decreases in the sandier substrate except for Ti and Ca. TRB are very high, caused by the high content of gypsum, also visible in the total amount and dominance of Ca and SO_4 in the water soluble ions. The exceptional high values of the AM-extractable cations are a result of a strong dissolving process of calcium carbonates and powdery gypsum during the extraction procedure resulting in high Ca contents.

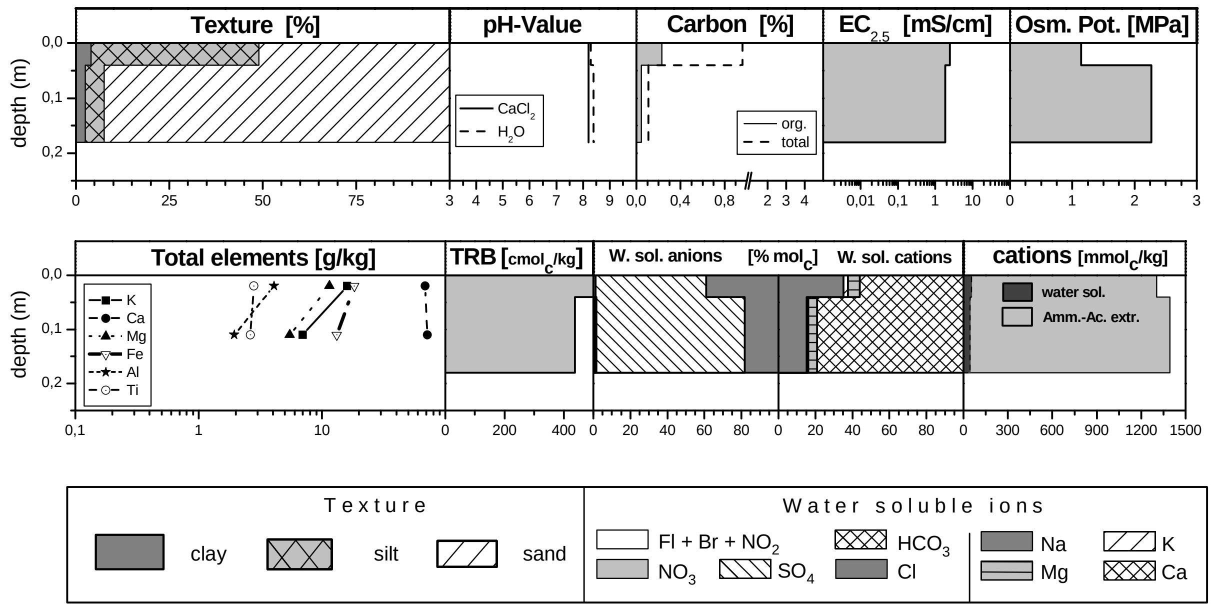


Figure 96 Properties of profile 540

3.8.3.4 Discussion of soil properties

Figure 97 depicts the variability of selected soil properties in two different depths intervals based on data of 20 profiles. The pH-values show a relatively small range with a concentration around 8.0 and no variation with depths. The same is true for the EC with typically values between 1 and 2 mS cm^{-1}. The lower values in pH and EC occur in the sandy soils of drainage courses with regular runoff events. Within the topsoil layer, the large range of organic carbon reflects the varying amounts of biological soil crust in the samples. Additionally, the silty wind induced material has higher OC values than the pure sands in the drainage courses. The fine particle percentage (clay & silt) varies strongly in the topsoil layer whereas the second horizon shows lower contents and a smaller variability. The rooting space (RS) is generally low and varies only slightly between the profiles.

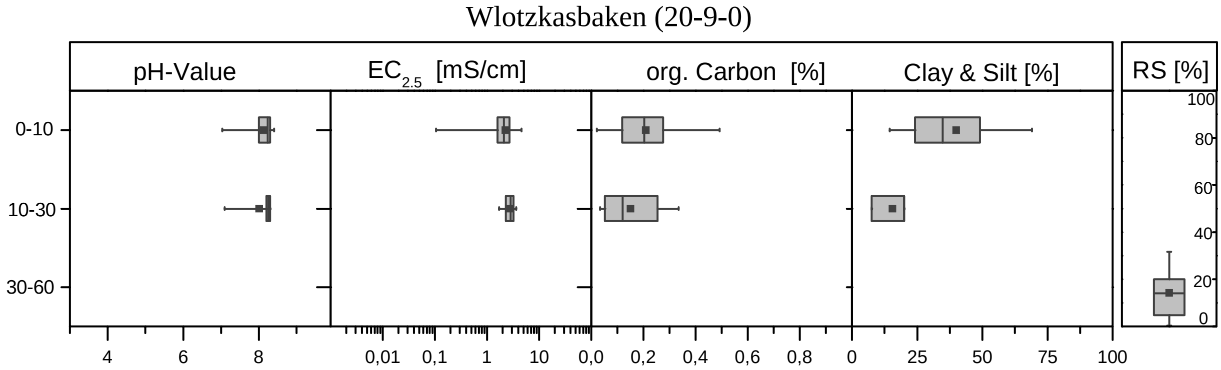


Figure 97 Variability of selected soil properties in two depth intervals for the observatory #16

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

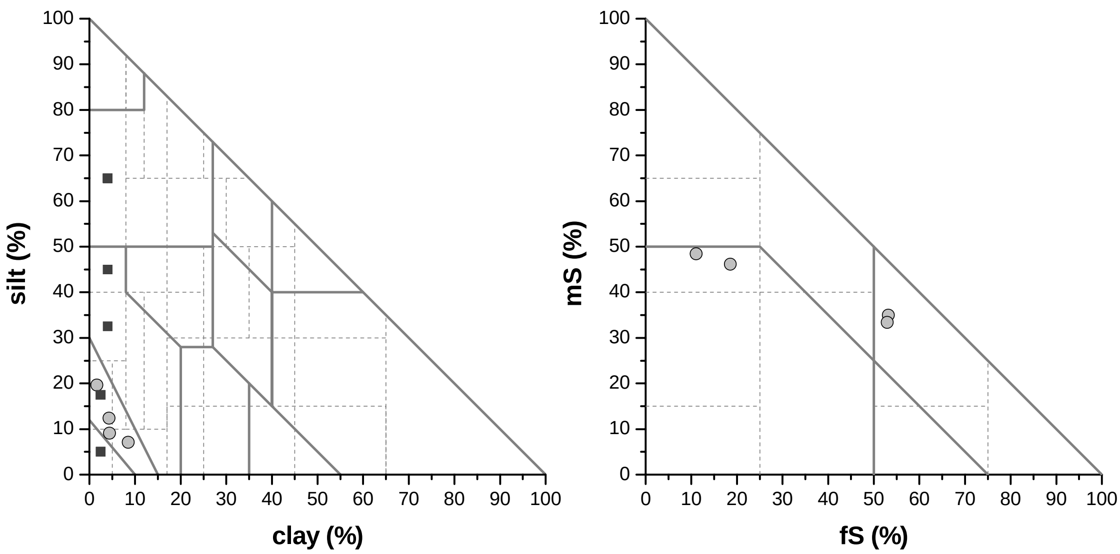


Figure 98 Results of the texture analyses for the observatory #16 Wlotzkasbaken

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 98 shows the results of the texture analyses for all samples of the observatory #16. Texture ranges from sand to silty sand and sandy silt. Clay contents are very low. With regard to the sand fractions, the samples can be split into two groups. The sand fraction of the silt rich and probably aeolian deposited topsoil material is dominated by > 50 % fine sand and some medium sand. The ‘subsoil’ or second horizons, which are derived from bedrock weathering, contain only few amounts of fine sand and consist mainly of medium and coarse sand.

Pattern analogies in the soil and vegetation distribution are not very prominent but evident and are analogous to topographic features. Higher plants concentrate along the drainage courses that i) receive more water by run-on effects and ii) have lower salt contents by run-off salt export. Although the annual rainfall amount is very low, a few events within decades suffice to transport at least the highly soluble salts into deeper topographical positions or even out of the system. They accumulate in pans or flow into the ocean. Within the observatory few depressions are highly enriched in soluble salts (NaCl, $EC_{2.5}$ = 15 mS cm^{-1}) resulting in an unstable surface which lichens are not able to colonise. These lighter coloured depressions are clearly visible due to their non-colonised quartz pebbles as shown in Figure 99.

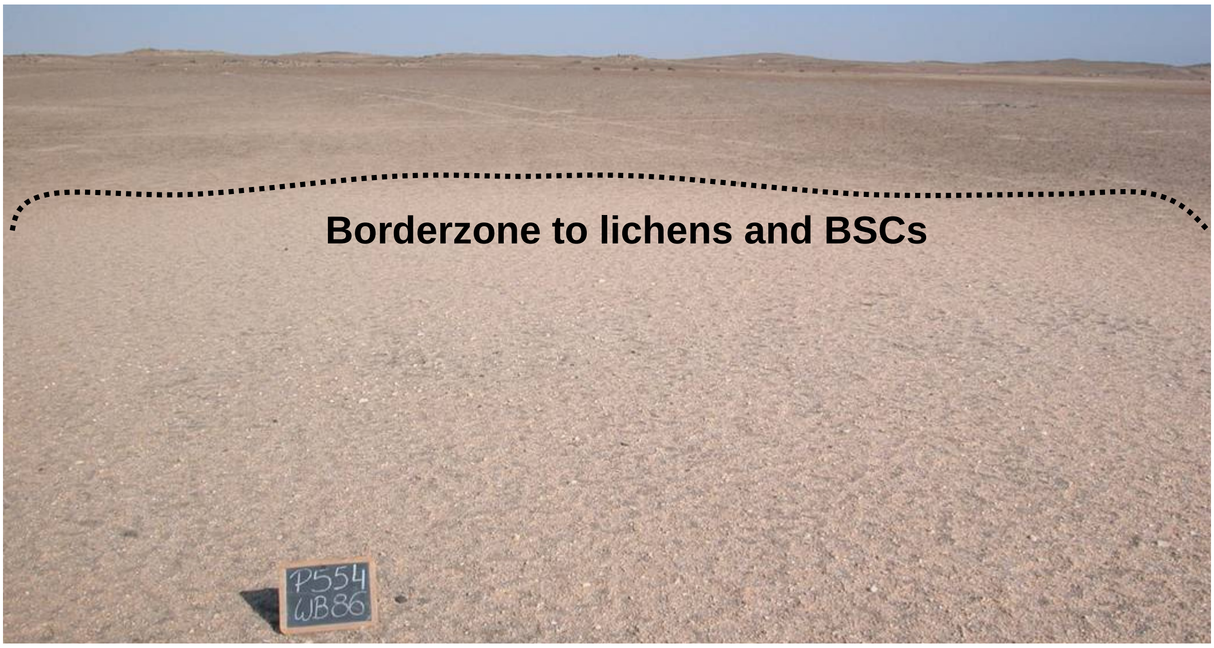
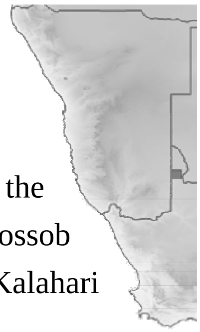


Figure 99 Slight depression with high salt contents and no lichens or biological soil crusts



3.9 Observatory 17 Alpha

3.9.1 Regional overview

The observatory #17 (Alpha) is situated on the private farm Alpha in the southwestern Kalahari in South Africa. The farm is located adjacent to the Nossob River approx. 30 km south of Twee Revieren, the southern gate of the Kalahari Gemsbok Park.

The region belongs to the Southern dunefield, one of the three main Kalahari dune regions, as described in numerous publications (e.g. THOMAS & SHAW 1991, BULLARD et al. 1997). The flat sand covered landscape is dominated by linear dune systems and is situated on a mean height of 1000 m asl. The region receives summer rainfall between 150 and 200 mm with an interannual variability exceeding 50 % (THOMAS & LEASON 2005, see also Figure 100). Mean annual temperature in the southern dunefield is around 20 °C with maxima of 45 °C in January and minima of -10 °C in July (at Twee Rivieren, VAN ROOYEN et al. 1990).

The most prominent features of the region, the NW-SE tending linear dunes, are comparatively small compared to the E-W orientated dunes of the northern Kalahari observatories. The dunes consist of narrow ridges, 5-25 m in height with crest to crest spacings ranging from 200 m – 2 km. According to the dune form classification for the south-western Kalahari by BULLARD et al. (1995), the dunes belong to the class 2 dunes characterised as ‘parallel /sub parallel dunes, which are continuous for several km and have only few Y-junctions and transverse elements’. The sands are rich in quartz and predominantly deep and structure less. Thickness of sand varies between 80 and 100 m interrupted by calcretes and silcretes (SCHNEIDER 2004). The dunes that are so characteristic of the Kalahari are believed to date back at least to the last glacial period and have been vegetated and stabilised since then. STOKES et al. (1997) give two periods of dune sedimentation in 10-17 ka and 28-23 ka by OSL methods. A more recent publication of THOMAS & SHAW (2002) synthesises and summarises the different data sets for the region.

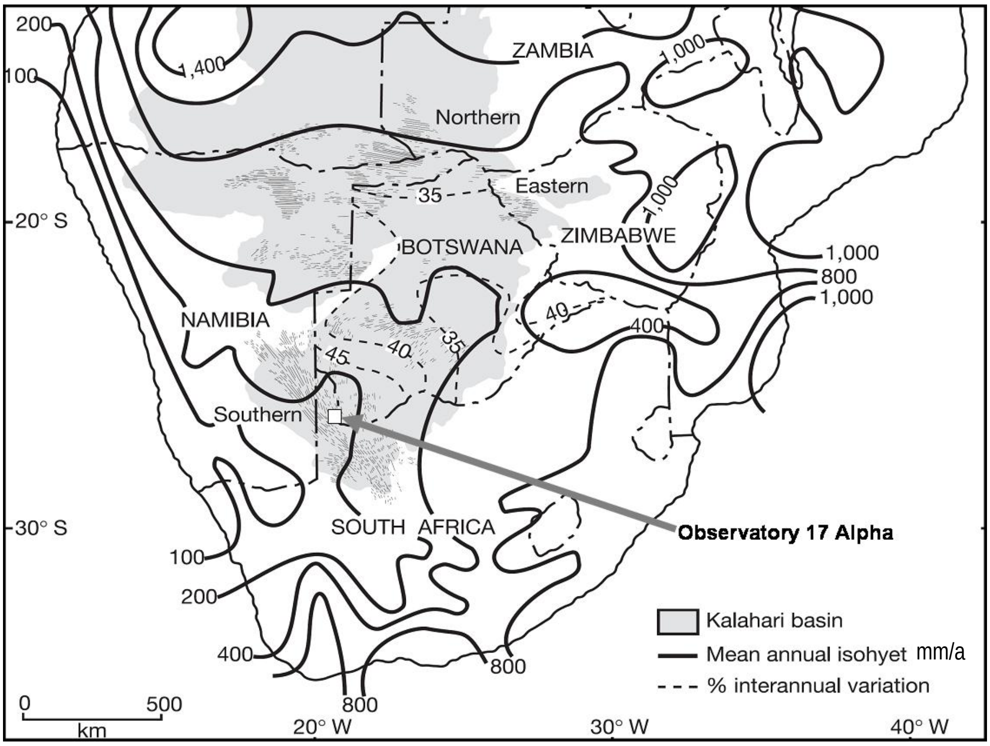


Figure 100 Overview of the Kalahari basin with the northern, eastern and southern dunefield and climatic settings (from THOMAS et al. 2005)

Further prominent features of the landscape are pans, calcretes and silcretes, which often occurr along the rivers Nossob and Molopo. The calcretes along the rivers are very thick and thus believed to have developed polygenetically by ongoing evaporation of Ca rich groundwater and dust input (GOUDIE 2002) (see Figure 101)

Figure 101 Massive Calcrete east of the observatory #17 Alpha along the Nossob river

The natural vegetation is characterised by an open grassland, dominated by grass species like *Schmidtia kalahariensis, Stipagrostis ciliata* and *S. obtusa*, with a sparsely shrub cover composed of *Acacia mellifera, A. hebeclada, Rhigozum trichotomum, Monechma spp*. and single larger trees (*Acacia erioloba, A. haematoxylon, Boscia albitrunca*) (VAN ROOYEN 2001).

The dominant land-use system in the southern dunefield is grazing with cattle and small stock on both, commercial farms and communal areas. The improved access to water in this environment free of natural surface water by drilling of boreholes has led in recent decades to intensive grazing. Main threat is overgrazing locally inducing processes of bush encroachment by *Acacia mellifera* and *Rhighozum trichotomun* and remobilisation of dunes by reduced vegetation cover. Today, the farm Alpha is a private nature reserve of 3,500 ha inhabiting an indigenous game population. Until ten years ago, cattle farming took place on the farm.

3.9.2 Observatory description

The observatory is situated approx. 1 km west of the Nossob rivier and 30 km south of Twee Rivieren (see Figure 102). As typical for the region, linear dunes with a mean height of 10 m and a mean spacing of 250 m from crest to crest stretches from SE to NW through the observatory. Mean height of the observatory is 896 m asl. Figure 103 depicts a topographic cross section through two dune valleys and its typical morphographic situation. As described by GOUDIE (2002), the dunes display an asymmetry with steeper flanks situated on the southwestern side.

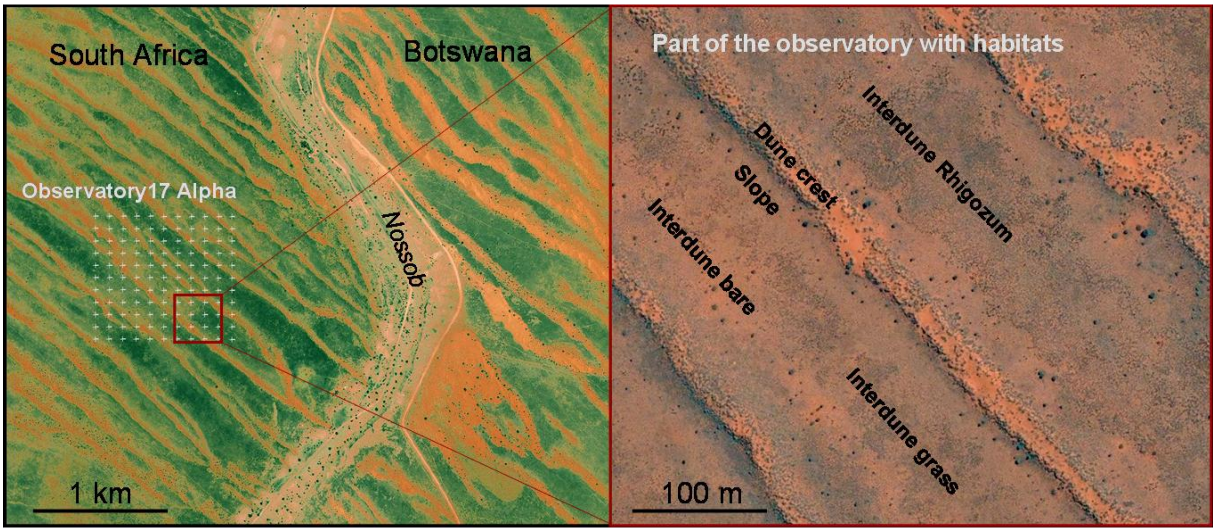


Figure 102 Left) Ikonos picture of the observatory #17 Alpha and surrounding
Right) Satellite view of the observatory #17 with chosen habitat types

The substrates on the observatory are aeolian sands above massive calcretes, which are in some interdune positions only shallowly covered. The typical aspect of the grass-dominated vegetation is shown in Figure 103. Dune crests are mainly dominated by *Stipagrostis amabilis* and occasionally accompanied by single shrubs or trees (*Acacia haematoxylon, A. erioloba, A. mellifera, A. hebeclada* and *Boscia albitrunca*) on the neighbouring flanks. The slopes consist predominantly of *Stipagrostis ciliata* and *Centropodia glauca*. *S. ciliata* can also be observed as the main species in the interdunes. Large parts of the interdunes are dominated by encroached patches of *Rhigozum trichotomum*. For a detailed species list, see also www.biota-africa.org.

Typical aspect of the linear dune system with grass dominated vegetation on the observatory 17 Alpha

Topographic transect from SW to NE across the dune system (vertical magnification 20x) (including ha 72, 63, 54)

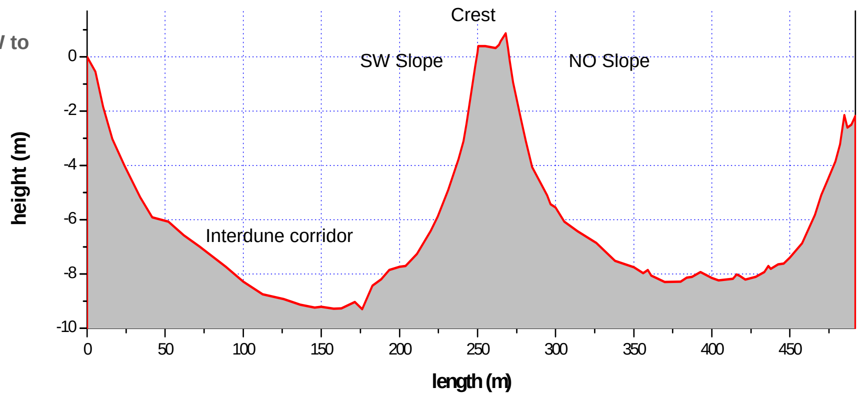


Figure 103 Vegetation aspect and topographic transect on the observatory #17 Alpha

Due to the strong correlation of topography with vegetation, the habitats were classified in i) dune crest, ii) dune slope and iii – v) interdunes that were subdivided in iii) grassy interdunes with *Stipagrostis spp.* and the annual *Schmidtia kalahariensis*, iv) a bush dominated aspect with *Rhigozum trichotomum* and v) a bare aspect with the dominance of *Dicoma capensis*. The habitats are shown exemplary in Figure 102.

3.9.3 Soils

3.9.3.1 Main soil units

By standardised procedure, 25 soil profiles were examined. Additionally, in order to gain insight in the topographical influence, a transect with 15 profiles was documented. The soil units of the observatory #17 (Alpha) and their distribution are provided in Figure 105.

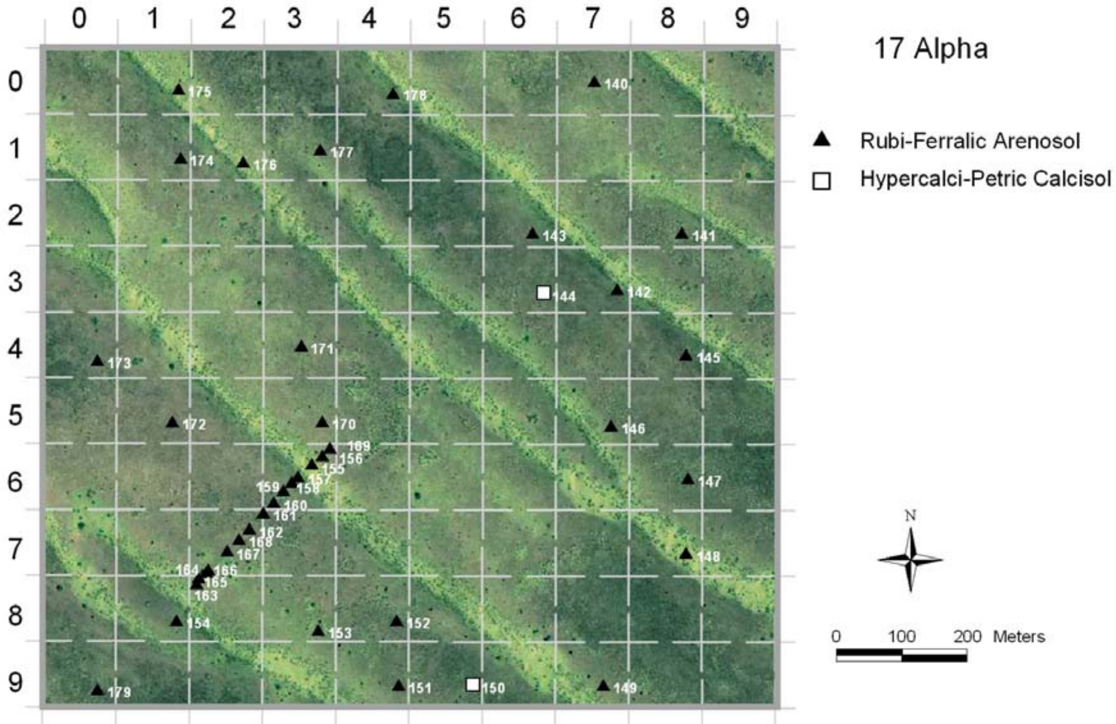


Figure 104 Distribution of soil units (WRB 1998, 2nd qualifier level) on the observatory #17 Alpha (Ranking 1-25 and additional transect) (Ikonos picture)

According to the WRB (1998), the reference groups Arenosols and Calcisols are found. Except for two Calcisols, all profiles are classified as Rubi-Ferralic Arenosols (Figure 105). This strongly expresses the uniform character of the reddish, sandy and nutrient poor substrate. A further distinction of the Arenosols is possible using the qualifiers 'dystric' 'eutric' and 'hypereutric'. Hypercalci-Petric Calcisols occur in two positions of the interdune corridors.

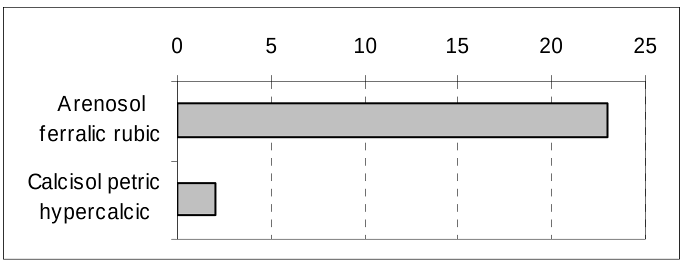


Figure 105 Frequency distribution of WRB (1998, 2nd qualifier level) soil units in obs. #17 Alpha

3.9.3.2 Remarks on classification

The classification of the soil units is given in the WRB (1998) nomenclature. The most important features and the differences of these soils (colour, sandy substrate, calcic horizon, and nutrient deficiency) could be described satisfactorily with this system. The definition of the calcic horizon is debatable due to its polygenetic history and the thickness, obviously unrelated to the overlying substrate. I decided to qualify calcrete as a petrocalcic horizon, because it provides the best expression of soil properties. Calcrete as bedrock would lead to a classification as Leptosol or in deeper variations as leptic Regosol that is less precise in the description value. The calcic horizon is the best way to express the differences of these profiles compared to the other Arenosols. With the application of the new version of the WRB (2006), only the ranking of the qualifier rubic and ferralic converts leading to Ferralic Rubic Arenosols as the main soil unit.

3.9.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **151**	Ha: **94**	Classification (WRB 1998)	**Rubi-Ferralic Arenosol (hypereutric)**
		(WRB 2006)	**Ferralic Rubic Arenosol (hypereutric)**

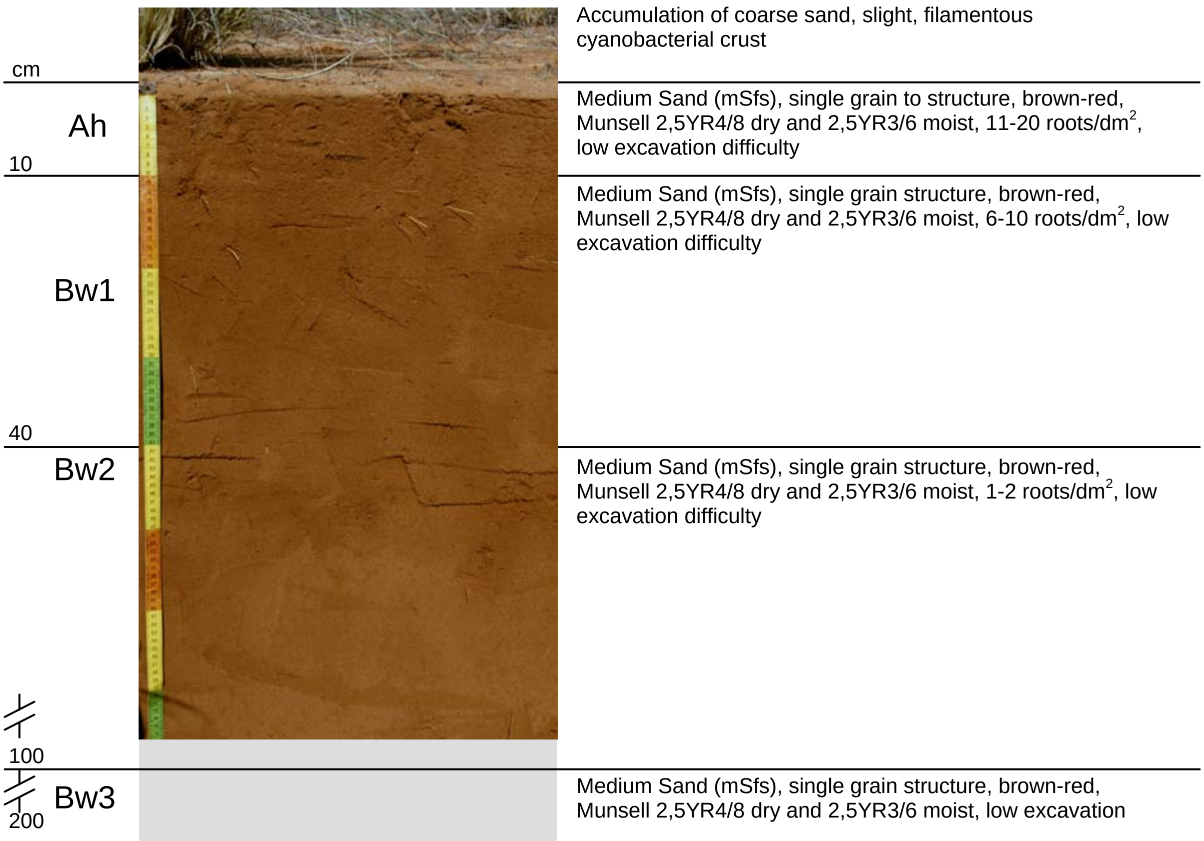


Figure 106 Description of profile 151

The Rubi-Ferralic Arenosol of Figure 106 is a characteristic example for the soils developed in pure and deep aeolian sands. The main texture of the profile is medium sand (mSfs) with only small amounts of silt and clay (< 3 %). Typically, the soil surface has a coarse sand cover and is slightly crusted with filamentous aggregations of cyanobacteria. The soil properties are markedly homogenous with depth, no variations in texture occur. The mean bulk density is 1.7 g cm^{-3}. The EC is very low with around 15 µS cm^{-1} and similar to the slightly acid pH-value stays constant over depth. Total element contents are low with highest values for K and Fe resulting in a mean TRB of 50 $cmol_c$ kg^{-1} underlining the nutrient poor, quartz rich sandy substrate. However, compared to the Kalahari sand of the northern Namibia observatories the sand is richer in nutrients. TRB values are even higher than interdune values of the observatory #02 Mutompo.

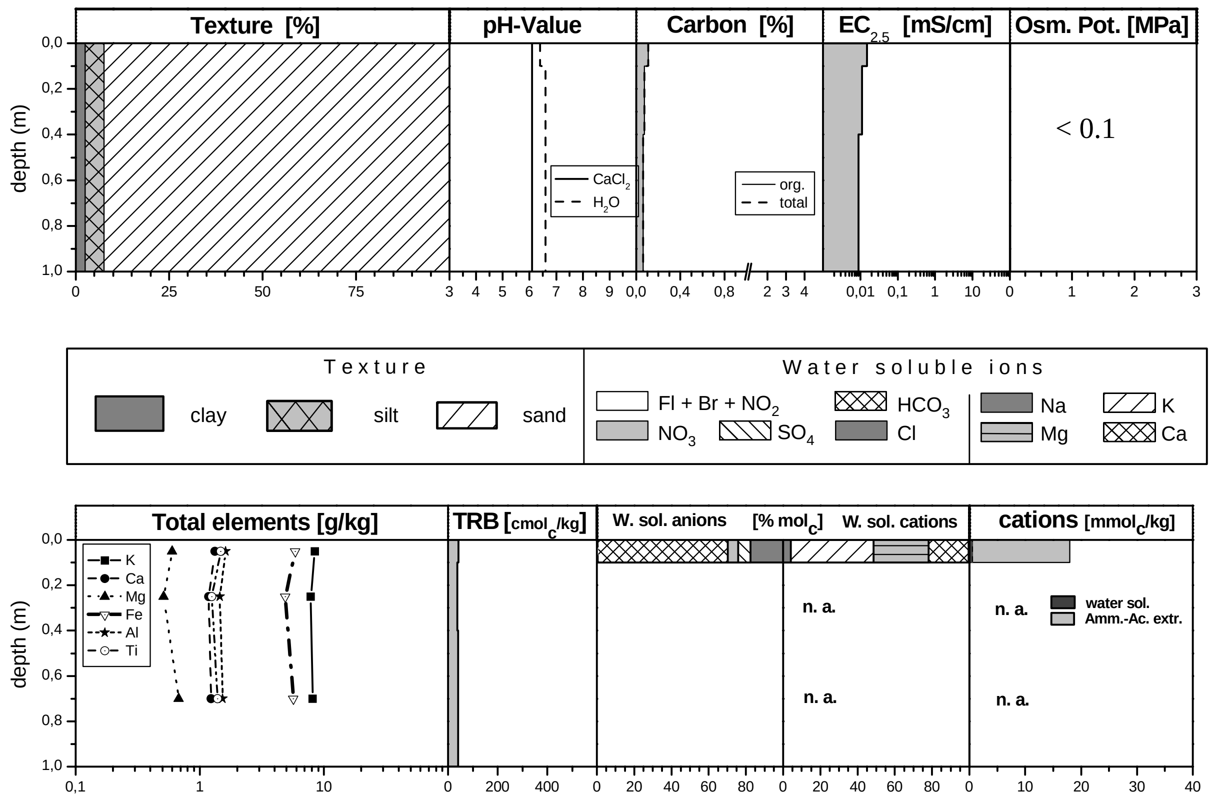


Figure 107 Properties of profile 151

Reference profile # 2

Profile: **150**	Ha: **95**	Classification (WRB 1998) **Hypercalci-Petric Calcisol**
		(WRB 2006) **Hypercalcic Petric Calcisol**

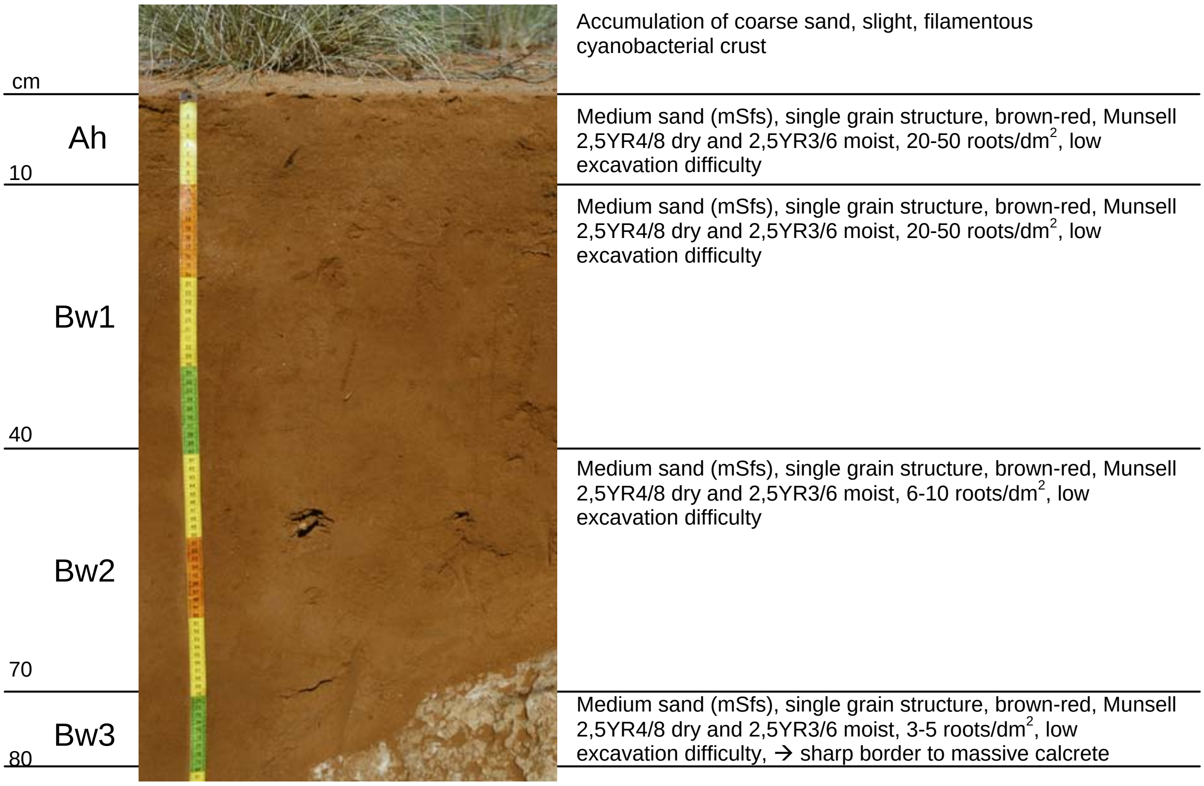


Figure 108 Description of profile 150

To the depth of 80 cm, the Hypercalci-Petric Calcisol of Figure 107 can be regarded as homogenous as reference profile 151. Underneath with a sharp border a massive calcrete or petrocalcic horizon occurs. Except for the total content of Mg increasing with depth, the soil properties are comparable to profile 151. Despite of the direct contact zone to the calcrete there are no prominent changes in the overlying horizon. This is interpreted as a lack of actual dynamics in the formation of the calcrete except for some dissolution with downward transport of the ions.

However, differences in water supply are anticipated, as the Calcrete reduces the ability to store plant available water. Vegetation on shallower Calcretes often tends to *Rhigozum trichotumum* patches.

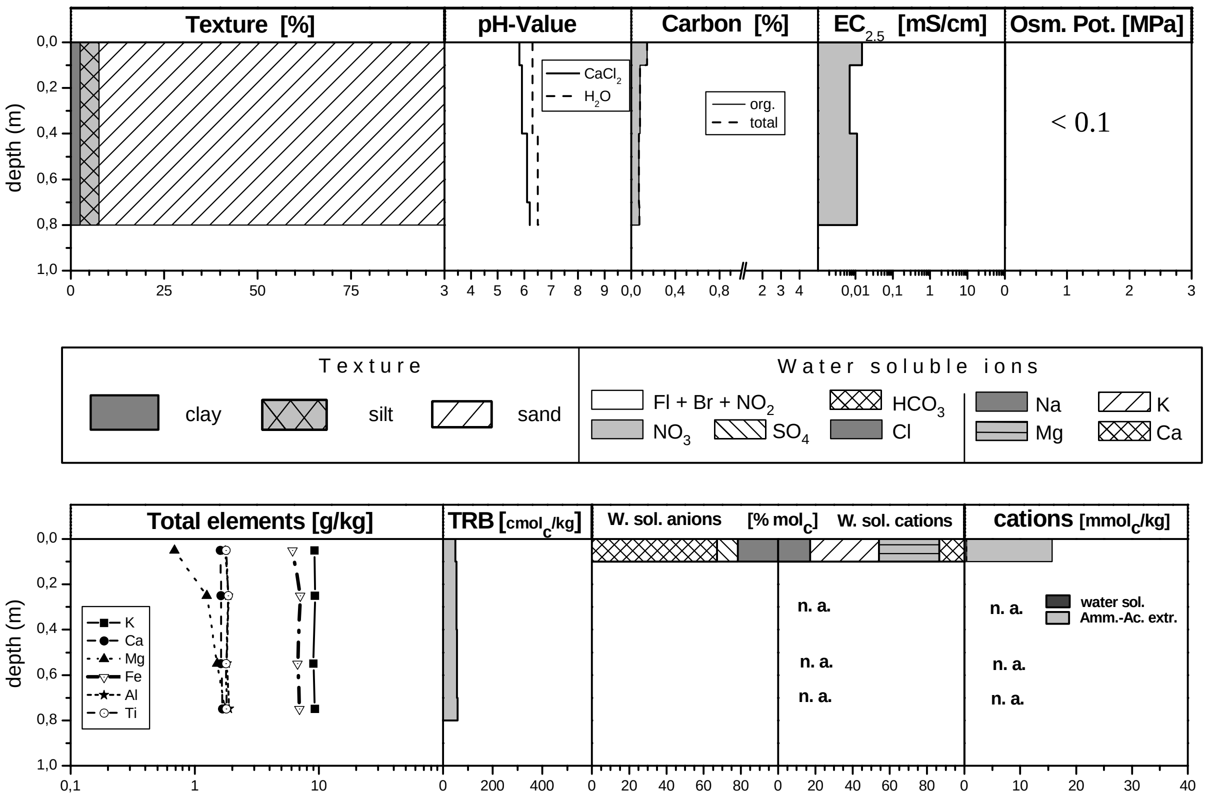


Figure 109 Properties of profile 150

3.9.3.4 Discussion of soil properties

Figure 110 depicts the variability of selected soil properties in three different depth intervals based on data of 25 profiles each. The pH-values show a relatively small range with a median at pH 6.0 and no variation with depths. $EC_{2.5}$ is very low (10-20 µS cm^{-1}) and varies only little with slightly higher values in the topsoil. Few outliers with values above 50 µS cm^{-1} are found under trees or bushes, which are preferred shady locations for animals and are thus slightly higher in nutrients. The generally extremely low values indicate leaching of nutrients, at least every few years, by strong rain events. Within the topsoil layer, the total content of organic carbon is slightly higher, but in general, there is no variation. The fine particle percentage (clay & silt) shows no range due to the pure sand substrate. The rooting space (RS) shows only small variations caused by two profiles with calcretes layers.

Texture is pure sand with nearly no silt and clay percentage (Figure 111). With regard to the sand fractions, the samples are predominantly medium and fine sands (mSfs, fSms). Coarse sand content is typically low, but a number of samples can be grouped as sands with increased coarse sand percentage. The spatial analysis showed that the occurrence of coarse sand tends to be higher in the SW exposed flanks and the neighbouring interdune. This is an indication of stronger wind impact and goes along with the asymmetry of steeper SW flanks.

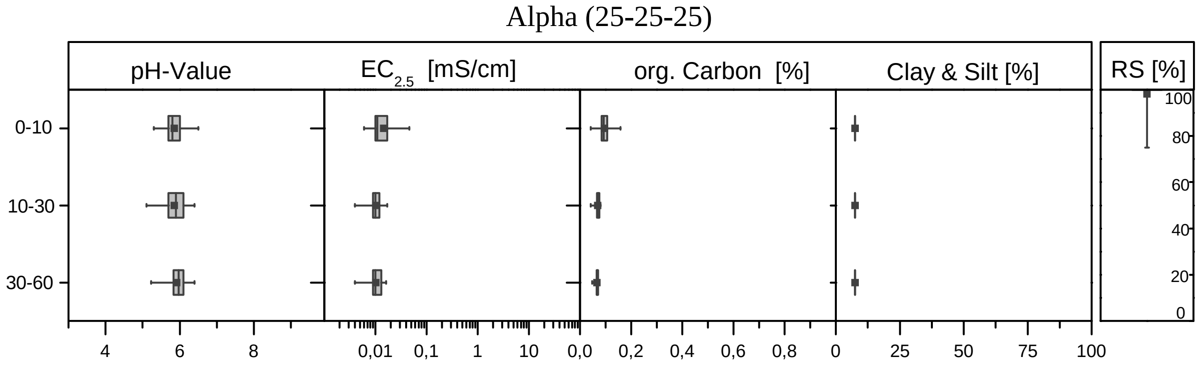


Figure 110 Variability of selected soil properties in three depth intervals for the observatory #17

Box = 25-75% with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top→ down), RS = rooting space

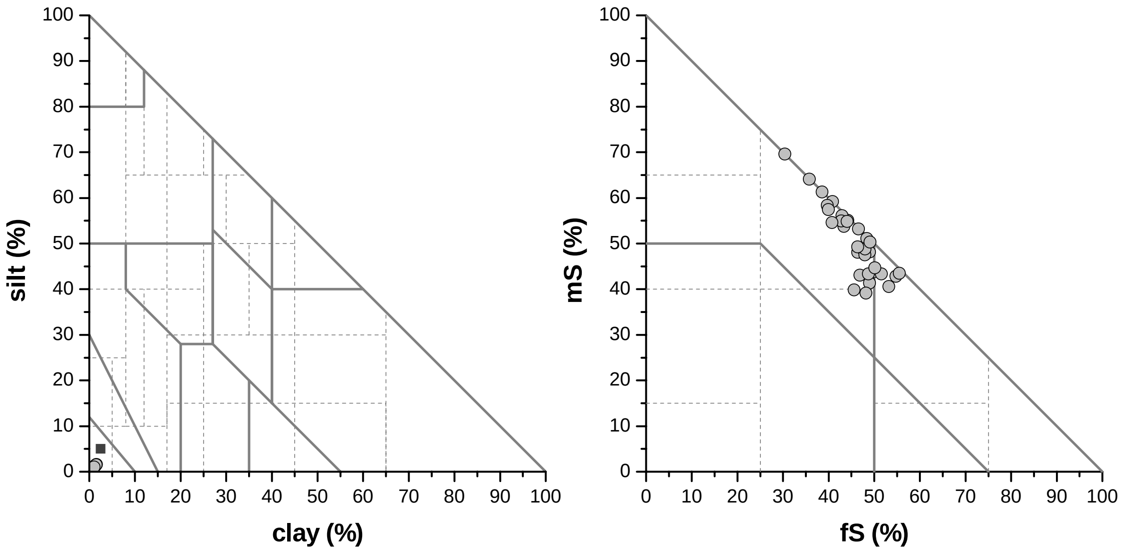


Figure 111 Results of the texture analyses for the observatory #17 Alpha

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Pattern analogies in the soil and vegetation distribution are not very prominent, but evident and linked to topographic features. They override the soil chemical properties, which are nearly constant on the observatory. Dune crests are regularly open habitats with dominance of *Stipagrostis amabilis*, a species adapted to moving sands. Upper slopes inhabit higher proportions of larger bushes and small trees, which obviously gain better water supply in these positions. This is probably due to the water storage capacity of the dune sand cushion that is not restricted to depth and can save deep infiltrated water for long periods. Deep rooting plants are able to 'tap' this resource. The different aspects of interdunes evident on the observatory reflect a combination of land-use history, game impact and soil physical conditions. The grassy interdunes having been subject to stronger grazing impact compared to other interdune sites show a dominance of the annual *Schmidtia kalahariensis* whereas the less frequented or remote sites are vegetated by *Stipagrostis ciliata*. Patches with *Rhigozum trichotumum* occur mainly combined with the occurrence of underlying calcretes but are most likely also a result of a stronger grazing impact. The patchy impact is well observable when looking at herds of Springboks that have preferred stands in the interdune sites and cause heavy trampling and grazing. Such strong animal impact can result in nearly bare interdunes mainly colonised by selected species such as *Dicoma capensis*.

Strongly related to the impact of trampling is the occurrence of cyanobacterial crusts that might play an important and long overlooked role in this nutrient poor system. Recently, research on the importance of biological soil crusts (BSC) and especially of the cyanobacterial crust was intensified (e.g. DOUGILL & THOMAS 2004, THOMAS & DOUGILL 2007). The studies reveal a high coverage of *Microcoleus vaginatus* cyanobacteria-crusts in different habitats and also emphasise the capability to rapidly re-establish after disturbance. Despite knowledge and classification of biocrusts there is still a lack of understanding the interaction between land-use, organisms and climate. For the Kalahari environment DOUGILL & THOMAS (2004) showed that, compared to other regions, the nutrient accumulation under bushes is only a result of biocrusts and not of nutrient richer dust input. They predominantly found this effect under *A. mellifera*, which provides an ideal combination for BSC development due to the protection from trampling while sufficient light reaches the ground due to their small leaves. Both factors advantage the bush in its nitrogen supply from the biocrusts. Once established this can be regarded as a self-energising system and is probably a key issue in understanding bush encroachment. However, as DOUGILL & THOMAS (2004) point out, the system should not be simplified, as at the same time, these *A. mellifera* bushes provide important safe sites for the seed production of grasses high in nutritional value in utilised systems.

Nutrient cycling or atmospheric nitrogen mining is not the only feature of these tiny organisms. In combination with the overall vegetation cover, *Microcoleus vaginatus* might play a crucial role for the resilience of the system according to its sensitivity for reworking the dune sediments in drought periods or the predicted climatic shift scenarios for the southern Kalahari (BULLARD et al 1997, THOMAS & LEASON 2005, THOMAS et al. 2005). In Figure 102, the impact of grazing is clearly observable by comparing the dunes on both sides of the Nossob rivier. On the eastern side, broad open dune crests with shifting sands have been created by heavy grazing pressure that not only caused disturbance in plant cover but also heavy impact on the stability of BSCs, as recently reported by THOMAS & DOUGILL (2007).

3.10 Introduction to the winter rainfall area

The observatories described below are all located in the Republic of South Africa and - in comparison to previously described observatories -, are dominated by a different rainfall regime: the winter rainfall. Although overall precipitation remains low, this is particularly true for the northern observatories. The different moisture regime favours a unique kind of dryland or desert, called the Namaqualand, which stretches from the Orange river in the north to the Olifants river. The Namaqualand covers approx. 50,000 km^2 (COWLING et al. 1999). Low but highly predicable rainfall, high diversity in soils (FRANCIS et al. 2007) and a moderate temperature regime throughout the year combined with a special evolutionary history are responsible for the unique plant diversity in the Namaqualand. The local flora mainly consists of dwarf, shallow rooted shrub communities with leaf succulence, winter growth phenology and high local and regional plant diversity with numerous centres of endemism (COWLING et al. 1999, DESMET 2007, DEAN & MILTON 1999).

3.11 The Richtersveld

Three observatories (#18, #20 and #21) are located in the arid northwestern part of the Namaqualand, a region called “Richtersveld” that belongs to the southern Namib desert. The area, named after a missionary who visited the region in 1830, can roughly be divided into four landscape types: the Orange River valley, the dune fields, the lowland plains and the mountain area. The mountainous area is the most famous landscape, the name Richtersveld stands for: a harsh mountainous desert. Geologically, the region provides its long history comprising a highly diverse lithology. The major tectonic units are the Namaqualand Metamorphic Complex and the Gariep Belt (FRIMMEL et al. 2001, detailed description in WILLER 2004).

Rainfall in the Richtersveld varies strongly within rather short distances although the winter rain events are more regional than local. This is due to the pronounced topography that favours and discriminates the amount of rainfall in front of and behind of the mountain chains. Annual precipitation varies in general from 50 to 150 mm with the majority precipitation being winter rainfall (GOTZMANN 2002). Summer rainfall also occurs regularly and affects the ecosystem through its erratic character causing high runoff and erosion. Coastal fog caused by the Benguela current occurs 90-140 days per year near the coast and moves inland regularly, especially in the Orange River valley. Similar to the central Namib observatory #16 Wlotzkasbaken, the wind regime is dominated by western and southwestern see-land winds, but especially in the winter months, the occurrence of strong easterly winds is responsible for high temperatures up to 45 °C and wind erosion phenomena.

The combination of topographic, lithologic and climatic variability leads to an enormous range of site conditions in terms of ecological niches for organisms. This resulted in high species numbers and a high rate of endemism (WILLIAMSON 2000). JÜRGENS (1991) provides the most detailed description of the flora of the Richtersveld. He distinguishes two major units, the Succulent Karoo with main elements of the Cape Floral Kingdom and the Nama-Karoo that is more affected by summer rainfall und contains mainly elements of the Paleotropis.

The northeastern and most mountainous part of the Richtersveld was made National Park in 1991. The local communities have the right to use the park for small stock grazing and are involved in nature conservation planning. Recently, the park became part of the Ai-Ais / Richtersveld Transfrontier National Park.

3.12 Observatory 18 Koeroegabvlakte

3.12.1 Regional overview

The observatory #18 (Koeroegabvlakte) is located in the Richtersveld National Park, now part of the Ai-Ais Transfrontier Park in the 'mountainous basin' structure of the Koeroegabvlakte. This 'basin' can be regarded as the upper catchment of the Kook rivier which drains eastwards towards the Orange river (see Figure 112) The region has a mean height of 400 – 600 m asl in the plains. Highest peaks reach up to 1000 m in the surrounding mountains that consist of granites and leucogranites of the Violsdrif Intrusive Suite. Annual Rainfall is around 120 mm with predominantly winter rainfall (GOTZMANN 2002).

Prominent features of the landscape are rounded, slightly elevated none or sparsely vegetated spots of 15 to 35 m diameters called 'heuweltjies' which means 'small mounds'. The occurrence of these mounds is widely spread throughout the coastal zone of the Namaqualand. Most authors consider the heuweltjies a remnant of past termite activity, but their origin is still not explained satisfactorily. A more detailed discussion of this topic is given in the description of the observatory #22 (Soebatsfontein).

The Koeroegabvlakte belongs to the Richtersveld bioregion of the Succulent Karoo and is characterised by the Northern Richtersveld Scorpionstailveld (MUCINA & RUTHERFORD 2005). The vegetation consists of a dwarf shrub community with various leaf succulent species such as *Ruschia spp.*, *Brownanthus spp.* and to some extent strongly degraded aspects with *Galenia spp.*. Degradation predominantly occurs around water points and active or inactive stockpost sites where the herders fence their stock over night.

Large parts of the region are affected by the occurrence of cemented soil material by silica (silcrete or duripan). These crusts are associated to 'heuweltjies' but also massive along the Kook river in the lower part of the Koeroegabvlakte. Another prominent micro feature of the landscape and often observable at riversides is a tiny (0.5 cm), greyish to black band or soil horizon, which has been found on several occasions throughout the Richtersveld (e.g. JÄHNIG 1993, JÜRGENS, pers. com.) in a depth of 30 -120 cm. A more detailed description is provided in the soil chapter.

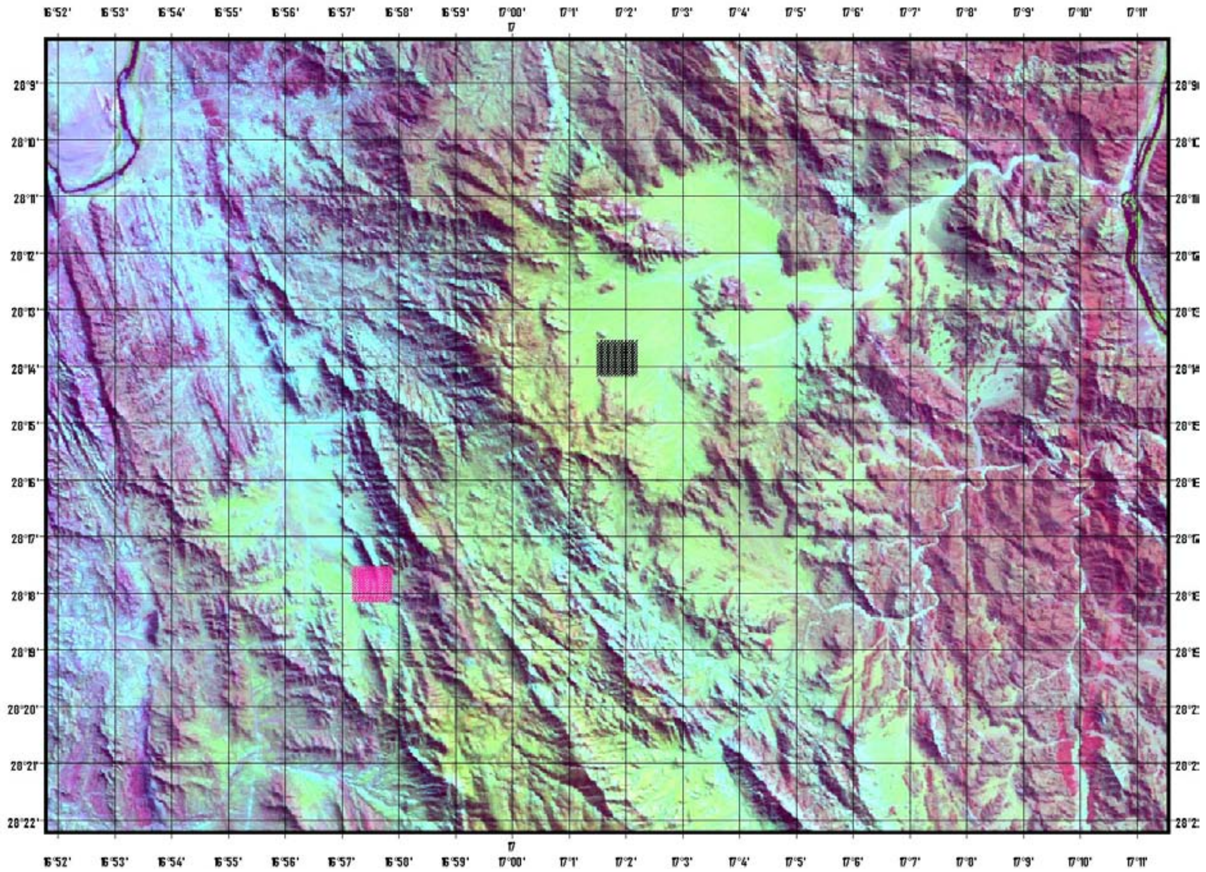


Figure 112 Overview of the central Richtersveld with the observatories 20 Numees (violet) and 18 Koeroegabvlakte (black), each 1 km^2 in size. Geodiversity is detectable by means of different colour of the Landsat image: west = Gariep Belt, east = Namaqualand metamorphic complex, each with different lithological units (Landsat 7 ETM, 7/4/1 RGB)

3.12.2 Observatory description

The observatory is located in the north bounding sinuosity of the Orange River (see Figure 112) in the upper region of the Koeroegabvlakte. As typical for the inner-mountain basin, the alluvial or mass transport derived materials are stretched in a fan structure from WSW to ENE throughout the observatory. The mean height of the observatory is 635 m asl with differences of 66 m from the SW corner to the NE corner resulting in a mean inclination of 5 %. An upper tributary of the Kook rivier is running through the observatory along the gradient.

Figure 113 provides a view of the observatory aspect. As typical for the whole region, the stable parts of the landscape are dotted with lighter rounded structures, namely the heuweltjies mentioned above.

Figure 113 Aerial view of the observatory #18 Koeroegabvlakte and surroundings. Clearly detectable are the bright patches of the heuweltjies. View direction from NE to SW, approx. 45° angle (perspective)

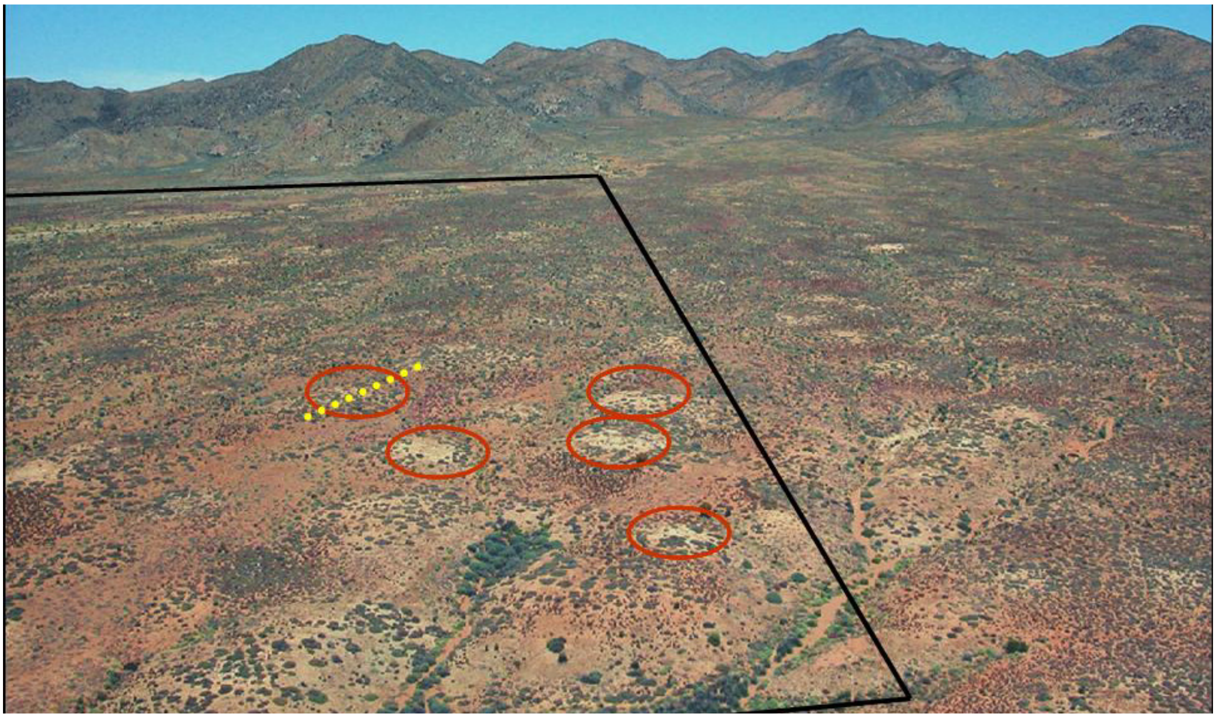


Figure 114 Vegetation aspect and marked heuweltjies on the observatory #18 Koeroegabvlakte (view southwards along the western border of the observatory)

The substrates on the observatory are mainly silty sands, partly underlain by cemented silcretes or larger boulders of the granites. In the rivier structure, pure coarse sands have accumulated. The typical aspect of the shrub-dominated vegetation is shown in Figure 114. Species distribution and over-all vegetation coverage are affected by the pattern of the heuweltjies and are typically patchy. The centres of heuweltjies are bare or colonised by single *Psilocaulon spp*. and many individuals of *Mesembryanthemum guerichianum*. Around these centres, *Brownanthius pseudoschlichtianus* is dominating, whereas in the matrix substrates *Euphorbia spp*., *Ruschia* and *Drosanthemum spp* are the most dominant genera. The eastern and southern part of the observatory seems to be stronger degraded with a higher occurrence of *Galenia spp*. For a detailed species list, see also www.biota-africa.org. On the observatory, only two types of habitats were distinguished: plain and rivier. Land-use in the Koeroegabvlakte is small stock grazing. Depending on the position of water points and stockposts, stronger overgrazed and degraded patches occur.

3.12.3 Soils

3.12.3.1 Main soil units

The regional and the frequency distribution of the soil units of 25 examined profiles is provided in Figure 115 and Figure 116.

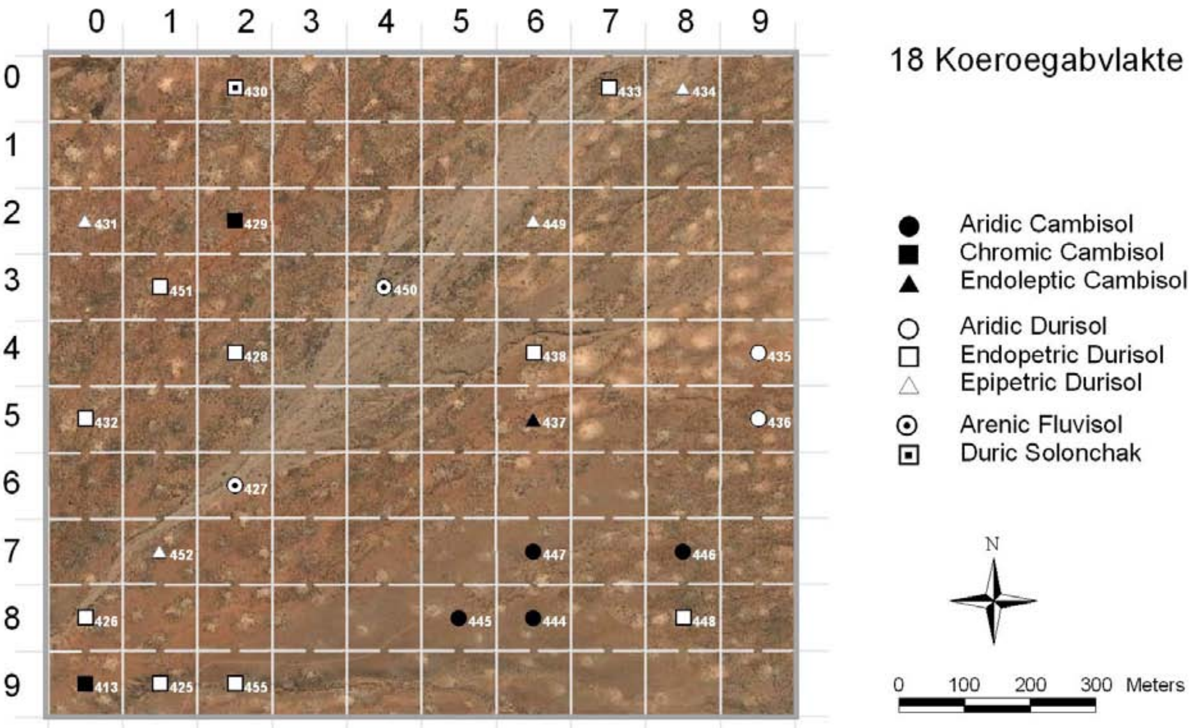


Figure 115 Distribution of soil units on the observatory #18 Koeroegabvlakte (WRB 1998, 1st qualifier level)

According to the WRB (1998), a relatively high number of 12 soil units on the 2nd-qualifier level associated with the reference groups Cambisol, Durisol, Fluvisol and Solonchak were found. Durisols are dominant followed by Cambisols; only two soils along the rivier exhibit fluvic properties and are thus classified as Fluvisols. One profile on a heuweltjie is strongly salt affected resulting in a Hypersali-Duric Solonchak. The depth of the duripan, the intensity of the reddish colour and the substrate qualifiers, mainly justify the differentiation of the Durisols and Cambisols. Durisols are associated with the heuweltjies and their surrounding rings of silcretes. The proportion of Cambisols is higher in the southeastern part of the observatory where most likely larger amounts of non-duric soil material accumulated after establishment of the heuweltjies and covers older duripans. Common features on the observatory are the calcareous fine earth and concretions in the heuweltjie structures, which are most likely of biogenic origin, as the soils have developed in a relatively base poor granite derived substrate.

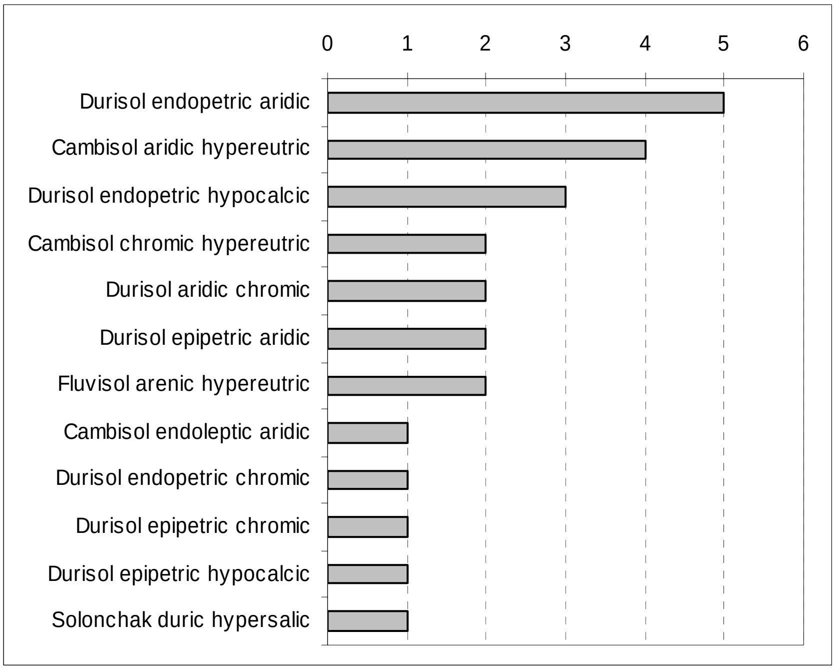


Figure 116 Frequency distribution of WRB (1998) soil units in obs. #18 (2nd qualifier level)

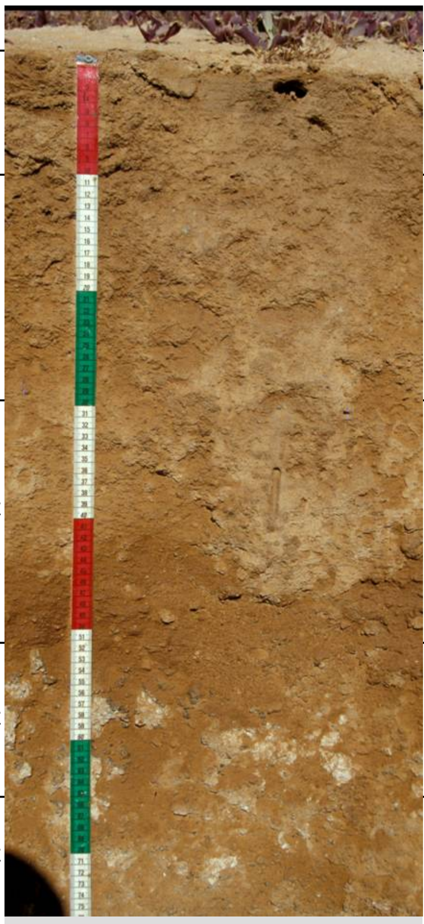
3.12.3.2 Remarks on classification

The classification of the soil units is provided in the WRB (1998) nomenclature. The most important features and the differences in these soils (depth limitations by duripans, colour, contents of salts and carbonates), could be described sufficiently with the provided qualifiers and reference groups. Within the heuweltjie structure, it is often difficult to decide whether the duripan or calcic features are diagnostic for the profile. The duric horizon overrides the calcic features in these cases, which can be expressed as Calcic Durisols. This was not possible due to the fact that in various profiles the content of calcium carbonate is too low for a calcic qualifier (< 15 %). On the other hand many soils are strongly affected by the presence of calcium carbonate, which should be possible to determine with the ‘calcaric’ qualifier to separate these soils from the carbonate free Durisols. This is not possible in the classification. The only possibility is the use of ‘hypocalcic’, which requires 5 % nodules or 50 % coverage by powdery lime. I generally applied the hypocalcic qualifier for Durisols when strong reaction with hydrochloric acid was observed. In case of salt accumulation, the salic horizon overrides the strong duripans and the profiles have to be classified as Solonchaks. The application of the new version of the WRB (2006) reveals only minor changes. Only the ranking of the qualifier duric and hypersalic changed in the Solonchaks and thus the frequency of Solonchaks will increase because of the reduced requirements for salic horizons. This enables a more detailed distinction between salt affected and none-affected soils.

3.12.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **430**	Ha: **02**	Classification (WRB 1998) **Hypersali-Duric Solonchak** (WRB 2006) **Duric Hypersalic Solonchak)**



cm	Horizon	Description
		Patches of microbiotic and physical silty crust, moderate penetration resistance (wet)
10	Ahk	Sandy loam (Su4) with coarse Sand (gSfs), subangular blocky to massive structure, moderately calcareous, greyish-light brown, Munsell 7,5YR8/4 dry and 7,5YR5/4 moist, 11-20 roots/dm^2, moderate excavation difficulty
30	Bwk	Sandy loam (Su4) with coarse Sand (gSfs), subangular blocky to massive structure, moderately calcareous, greyish-light brown, Munsell 7,5YR7/4 dry and 7,5YR5/4 moist, 21-50 roots/dm^2, moderate excavation difficulty
52	Bwkqcz	Sandy loam (Su3) with coarse Sand (gSfs), cemented structure, durionodes, moderately calcareous, brown, Munsell 7,5YR7/4 dry and 7,5YR5/6 moist, 11-20 roots/dm^2, high excavation difficulty
65	Bwkqcz	Sandy loam (Su3) with coarse Sand (gSfs), cemented structure, durinodes, strongly calcareous, greyish-brown, Munsell 7,5YR6/4 dry and 7,5YR4/6 moist, 11-20 roots/dm^2, high excavation difficulty
90	Bwkqcz	Sandy loam (Su3) with coarse Sand (gSms), moderately calcareous, durinodes, greyish-brown, Munsell 7,5YR7/4 dry and 7,5YR5/6 moist, 11-20 roots/dm^2, moderate excavation difficulty

Figure 117 Description of profile 430

The Hypersali-Duric Solonchak of Figure 117 is a rare soil unit on the observatory that was selected as this profile exhibits many typical features for heuweltjies positions in the whole set of profiles. The second reference profile will represent the other side of feature ranges. Thus, the soil properties in the observatory can roughly be classified as a ranging between these two reference profiles.

The Solonchak is located in the northern part of the sloping plain composed of weathered substrates of the Violdrif Granites system just at the centre of a heuweltjie. The main texture of the profile is silty sand (Su) with a relatively evenly distributed sand fraction and a slight dominance of coarse sand. The silt fraction is predominantly characterised by coarse silt. As typical for calcareous materials, the soil surface is fixed weakly by a dark cyanobacterial crust.

The soil is strongly saline ($EC_{2.5}$ 0.5 - 4 mS cm^{-1}, increasing with depth) and very strongly alkaline in the top 50 cm above a moderate alkaline subsoil. Inorganic carbon reaches 2 % in the topsoil and decreases slightly with depth. Organic carbon amounts to 1 % in the topsoil and 0.3 % in other horizons. The strongly saline conditions are responsible for high osmotic potentials (OP) up to 2 MPa under field capacity conditions. The total element contents are constant over depth indicating homogenous parent material except for Ca and Mg that show the same trend as inorganic carbon. Both TRB and the amount of water soluble salts are very high with high proportions of nitrates (119 – 941 mg kg^{-1}).

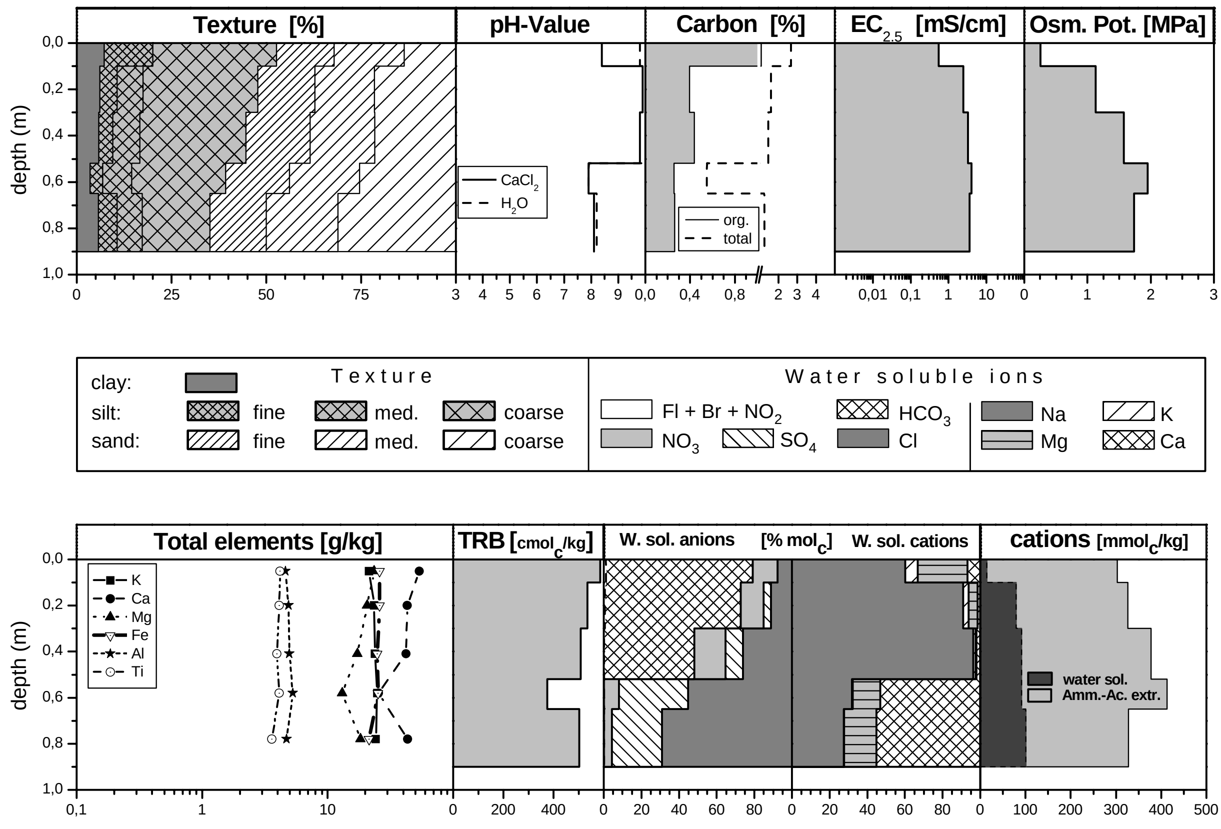
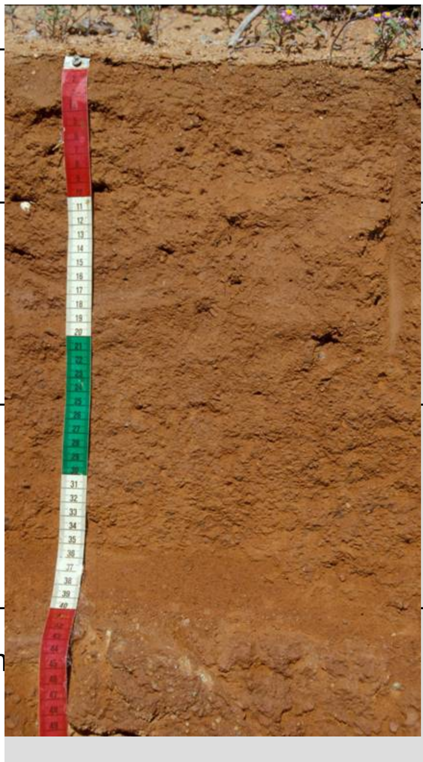


Figure 118 Properties of profile 430

Reference profile # 2

Profile: **431**	Ha: **20**	Classification (WRB 1998)	**Chromic - Epipetric Durisol (Hypereutric)**
		(WRB 2006)	**Epipetric Durisol (Chromic)**



cm	Horizon	Description
		Moderate penetration resistance (wet)
10	Ah	Sandy loam (Su3) with coarse sand (gSfs), subangular blocky structure, greyish-reddish-brown, Munsell 7,5YR5/8 dry and 7,5YR4/4 moist, 21-50 roots/dm^2, low excavation difficulty
25	Bw1	Loam (Slu) with coarse sand (gSfs), subangular blocky structure, reddish-brown, Munsell 7,5YR5/6 dry and 7,5YR4/4 moist, 11-20 roots/dm^2, moderate excavation difficulty
40	Bw2	Sandy loam (Sl3) with coarse sand (gSfs), subangular blocky to cemented structure, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 11-20 roots/dm^2, high excavation difficulty
50	Bwqm	cemented structure, very high excavation difficulty → duripan

Figure 119 Description of profile 431

Compared to the previous profile, the Chromi-Epipetric Durisol of Figure 119 represents the opposite side of ranges in typical soil features for the Koeroegabvlakte. The profile is positioned in the matrix between the heuweltjies and has a strong reddish, non-calcareous and non-salty character. The occurrence of a duripan below the depth of 40 cm restricts the available rooting space. The texture (silty to loamy sand) is constant over depth and shows higher clay contents than the previous profile. The non-saline character is expressed by very low EC values of 20 – 50 µS cm^{-1}. The pH-value is moderately alkaline and constant with depth. Carbon contents are very low and the constancy of the total element concentrations indicate the homogenous parent material of weathered granite material. As EC indicates, the amount of water-soluble salts is very low contrary to the fairly high AM-extractable cations.

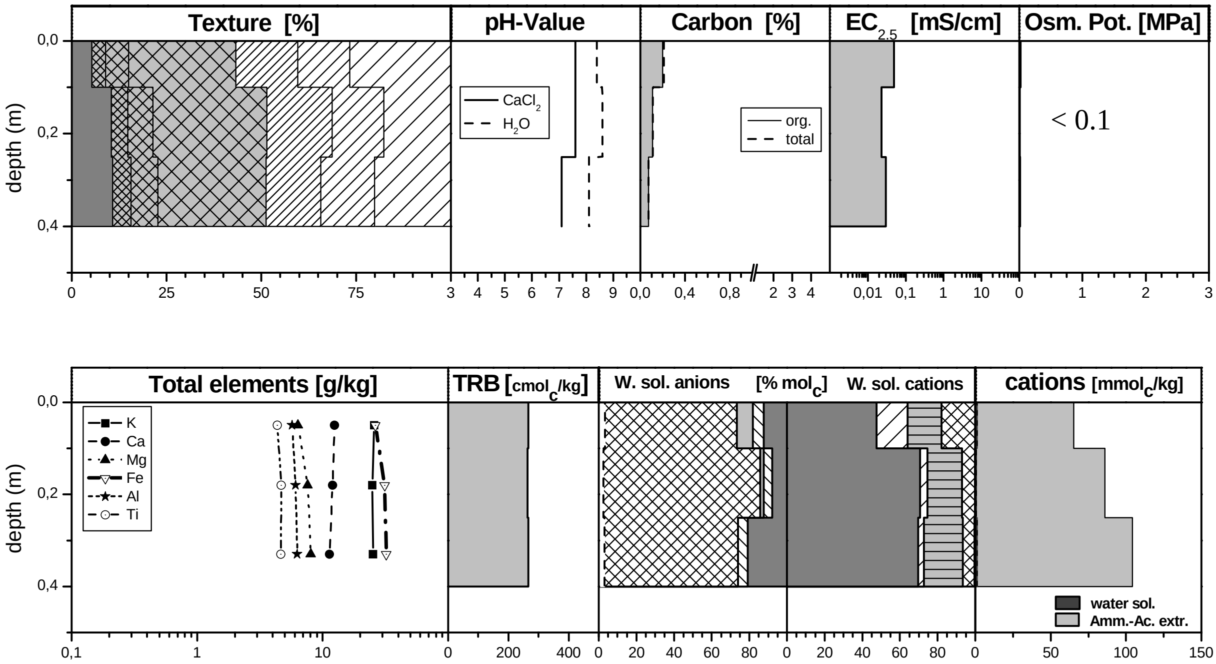


Figure 120 Properties of profile 431

3.12.3.4 Discussion of soil properties

Figure 121 depicts the variability of selected soil properties in three different depths intervals based on the data of 25 profiles. Due to the dominant ions in the soil solution (Na – HCO_3), the pH-values show a concentration of values around pH 8.0 but oscillate widely around this value, in particular in the subsoil. EC also shows a wide range of values, especially in the subsoil, but the median values indicate a generally low content of soluble salts increasing with depth. Increased mean values and strong salinity in single sites are the result of samples in the heuweltjie centres, which are always nutrient (and carbonate) enriched. Organic carbon shows a wide range in the topsoil and decreasing contents and variability with depth. The fine particle percentage (clay & silt) varies across all depths due to the combination of pure sand substrate in the rivier and strongly silty sands in the heuweltjies. The rooting space (RS) fluctuates for both the coarse fragment proportions (durinodes and fine and medium gravel from granitic substrates) and the depth of duripans, which are regarded as root restricting.

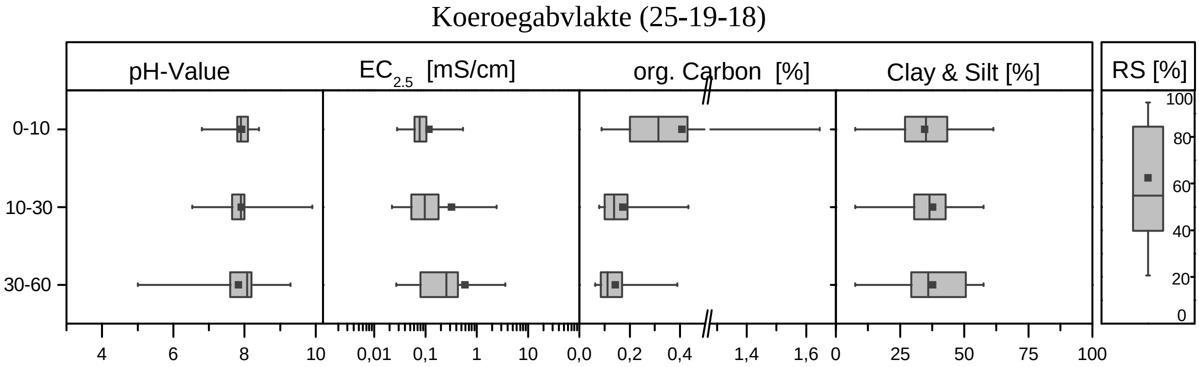


Figure 121 Variability of selected soil properties in three depth intervals for the observatory #18

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

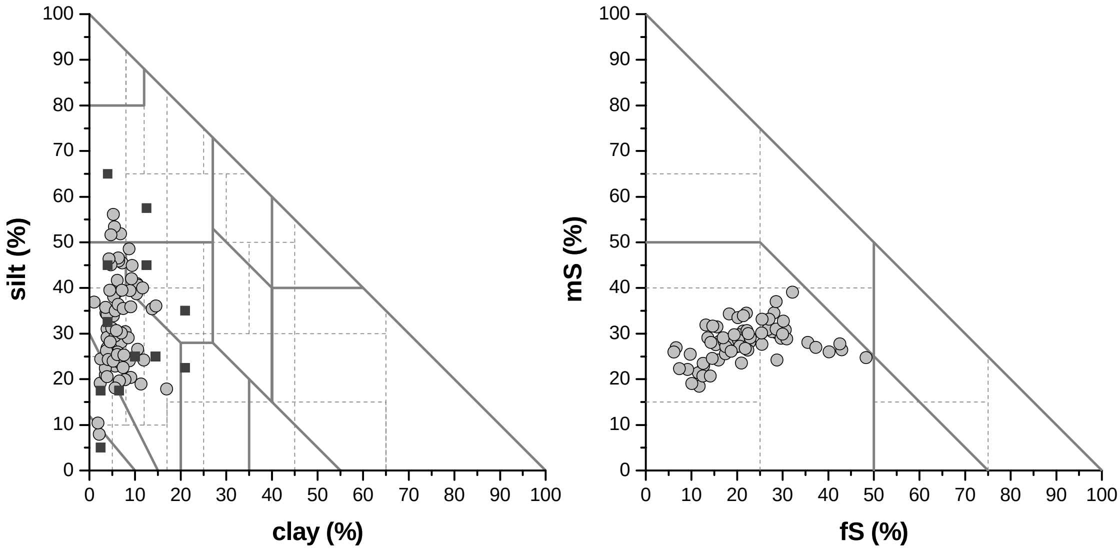


Figure 122 Results of the texture analyses for the observatory #18 Koeroegabvlakte

squares = finger test (all samples)and circles = lab analyses (selected samples)

Figure 122 shows the results of the texture analyses of all samples for the observatory #18. Texture is mainly silty and loamy sand with coarsest values for the river profiles and highest silt contents in the heuweltjies. With regard to the sand fractions, the samples are predominantly coarse sands with equal contents of fine and medium sands (gSms, gSfs), as typical for such granitic derived materials that had experienced only short-distance transportation.

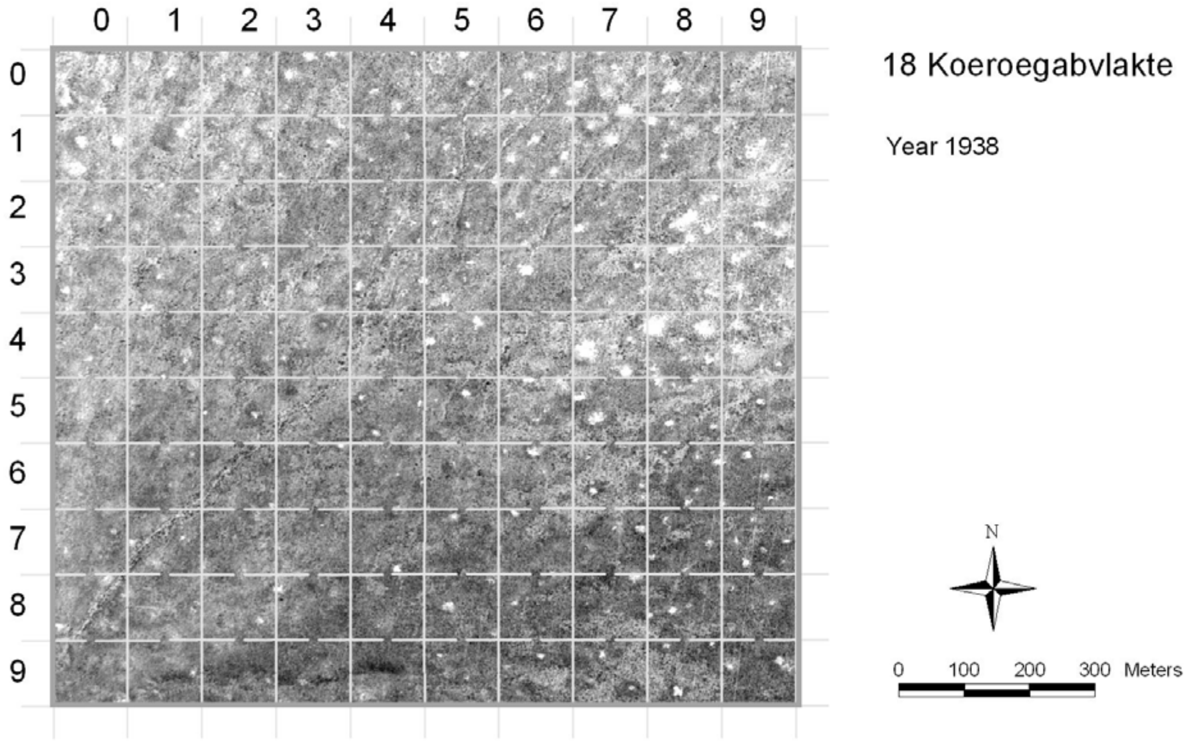
Tab. 4 Analyses of a microtransect with 5 profiles through a heuweltjie structure in the observatory #18. Results are means of all horizons in each profile

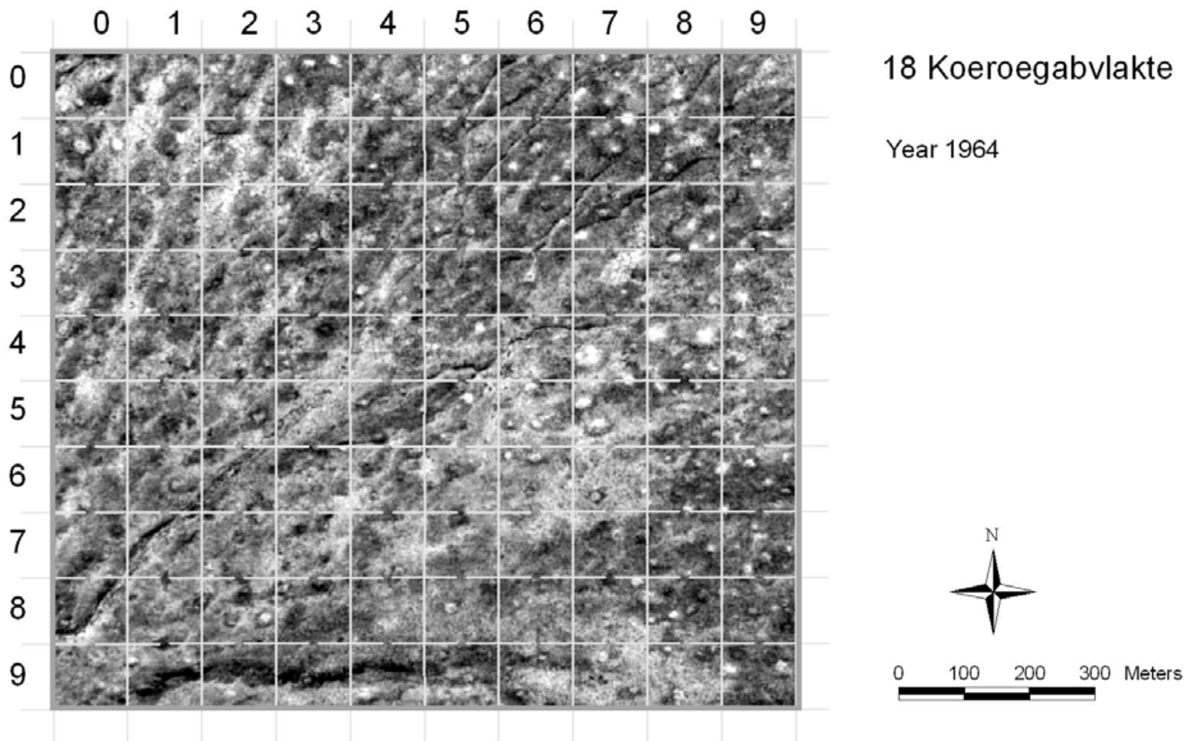
HEUWELTJIE KOEROEGAPVLAKTE

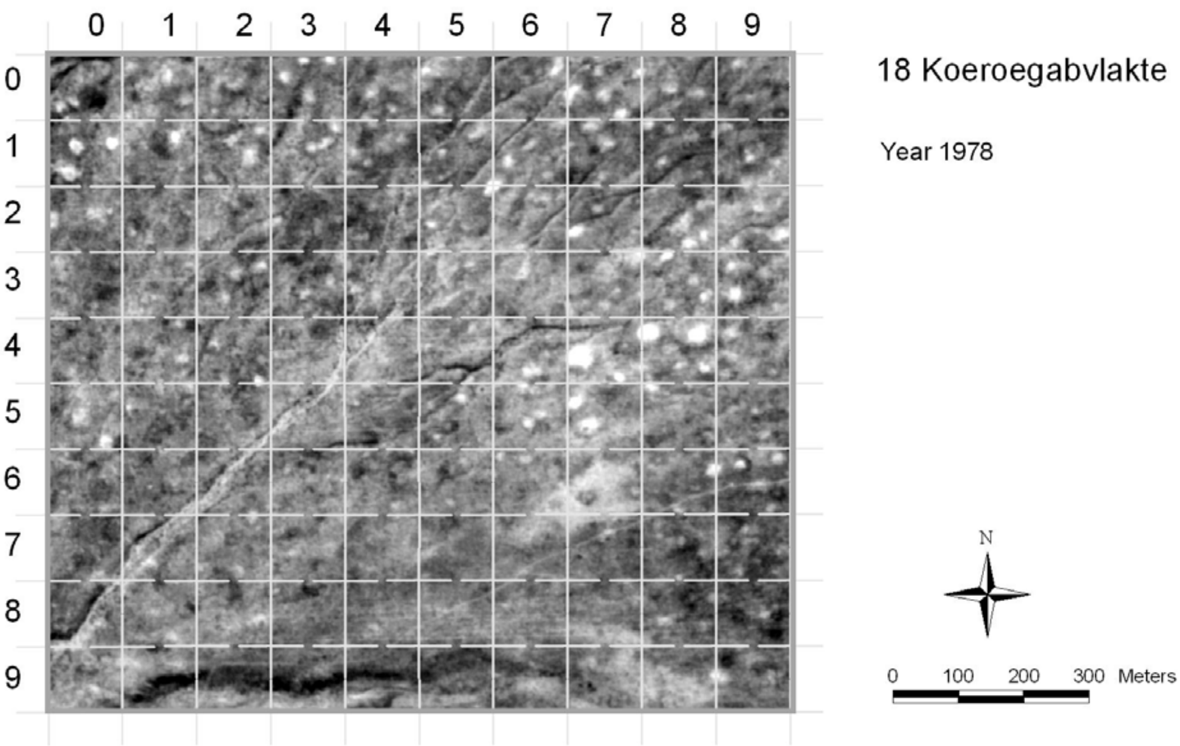
Parameter	Unit	Matrix	Slope	Centre	Slope	Matrix	Median of region
distance to centre	m	15	7	0	-5	-12	
Clay	%	5.8	n.a.	8.7	8.0	6.4	n.a.
Silt	%	29.9	n.a.	42.8	41.0	24.7	n.a.
Sand	%	64.3	n.a.	50.0	49.5	68.7	n.a.
pH ($CaCl_2$)	pH	6.8	8.0	8.0	8.4	7.4	7.9
$CaCO_3$	%	0.0	0.2	2.1	3.7	0.0	0.01
EC_e	mS/cm	0.3	2.0	8.3	17.2	0.4	1.0
Ca	g/kg	11.3	12.5	20.6	29.7	13.6	16.0
Mg	g/kg	4.7	6.1	14.6	19.5	6.6	7.8
Crusts	-	Duripan	Durinodes	Durinodes	Durinodes	Duripan	-

Pattern analogies in the soil and vegetation distribution are well observable. Regarding soil features, this is most evident on a small scale in the concentric pattern of different species communities on and around heuweltjies. Tab. 4 shows the results of a soil transect through a heuweltjie. Except for sand, all selected parameters show a strong increase towards the centre of the heuweltjie. The accompanying change in plant species is a result of both soil chemical properties and soil physical effects caused by duripans. These silica-cemented horizons are found around heuweltjies and are believed to be a result of silica precipitation caused by drying processes or lower ph-values outside the termite influenced heuweltjie. This topic is described and discussed more detailed for observatory #22 (Soebatsfontein).

Several features of the landscape are significant due to processes of change. The most evident is the erosion in form of gullies, which affect large parts of the observatory and other parts of the Koeroegabvlakte (see also GOTZMANN 2002). It is not clear whether these erosion processes are favoured i) by stronger rainfall intensities due to an intensification of summer rainfall or ii) by reduced vegetation cover from overgrazing or iii) by a combination of both. Another prominent feature is the occurrence of many dead individuals of the shrub *Zygophyllum prismartocarpum* in the area east of the observatory. Here it is in discussion whether this is caused by overgrazing, by the change in environmental conditions or by a natural dynamic within the community structure. A third feature is the vegetation pattern on the heuweltjies. The observation of various bare or only sparsely vegetated patches led to the hypothesis that these structures are a result of dynamics over the years by disturbance processes caused by small mammals for instance. If so, this would then result in a changing pattern of the bare patches in the landscape. To follow up this hypothesis, I analysed a sequence of aerial photographs, starting in 1938 with pictures in 1964, 1978, 1997 and 2004 (see Figure 123). The analysis showed that no turnover in the pattern of bare and vegetated heuweltjies was evident within the last 70 years. The bare patches are rather a result of soil features (salt and carbonate accumulation) which did not change over this period. The aerial photograph analysis further revealed an increase in size and visibility of the rivier structure in the observatory. This is interpreted as further proof for the increasing pressure on soil resources by erosion processes.



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18 Koeroegabvlakte
Year 1978
N
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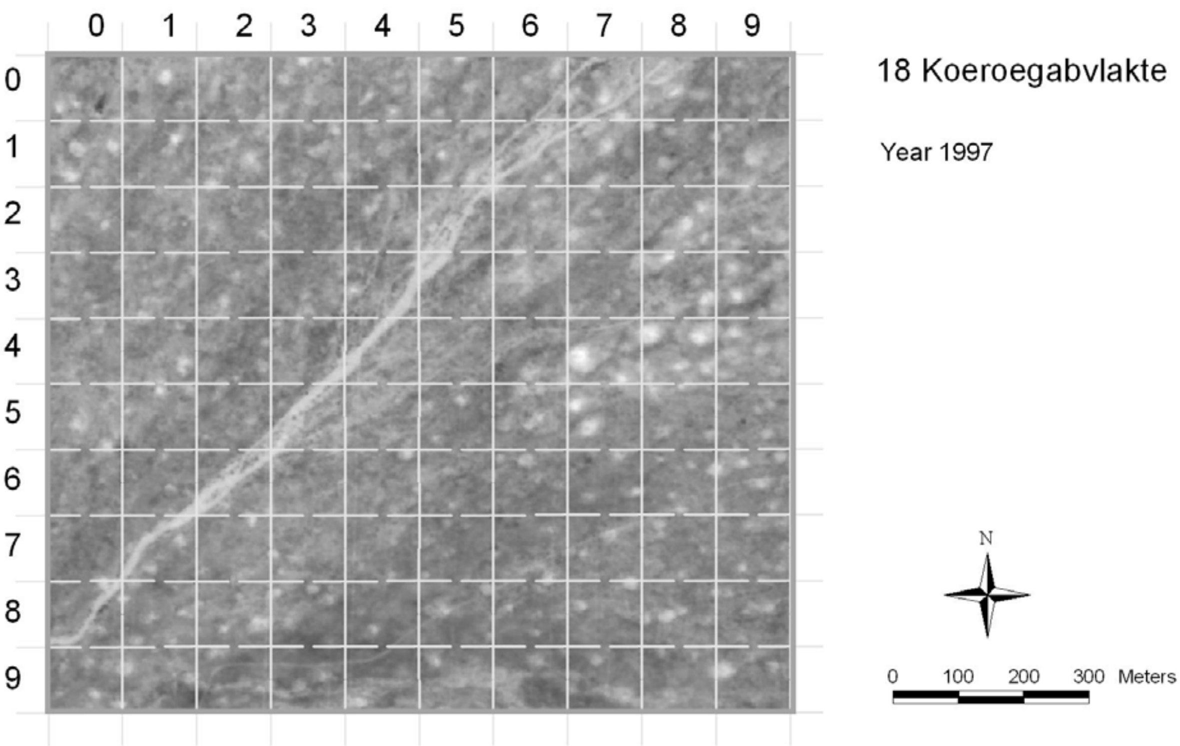
0
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18 Koeroegabvlakte
Year 1997
N
0 100 200 300 Meters

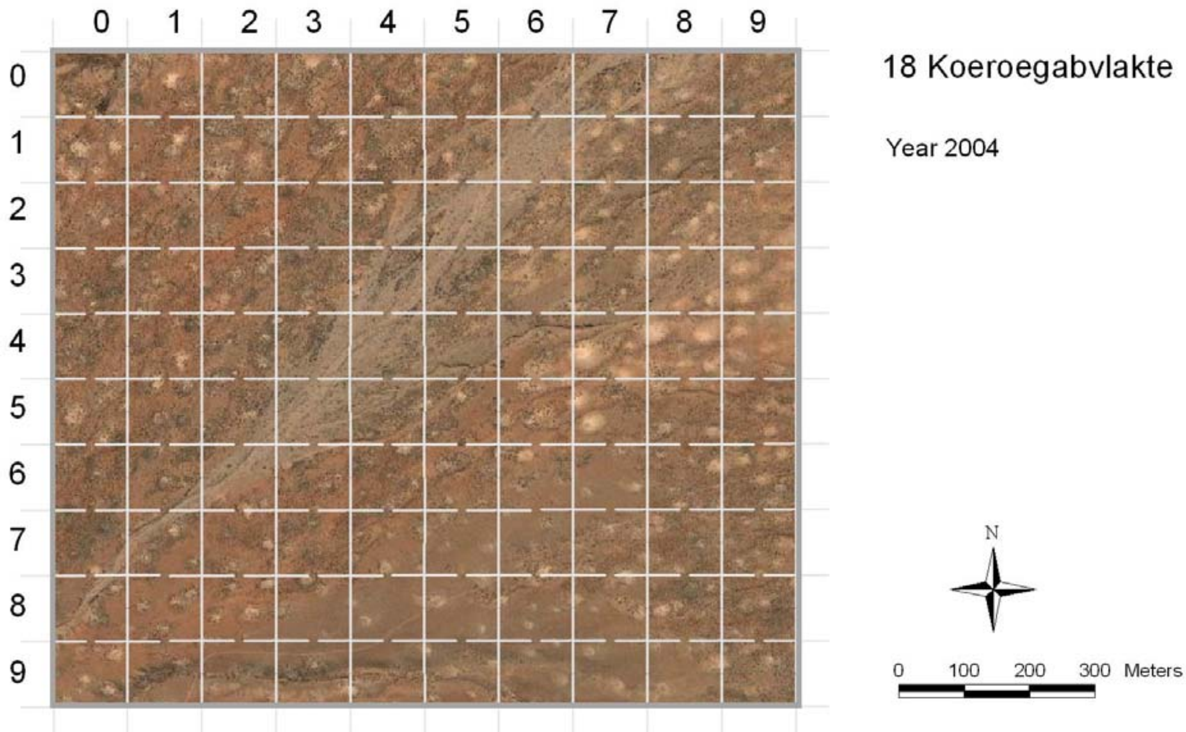


Figure 123 Sequence of aerial photographs of the observatory Koeroegabvlakte (1938-2004)

A prominent micro feature of the landscape, which is often observable at riversides is a tiny (0.5 cm), greyish to black band or soil horizon. It has been found on several occasions throughout the Richtersveld (e.g. JÄHNIG 1993, JÜRGENS, pers. com.) in a depth of 30 - 120 cm. This study also shows that several profiles inhabit this horizon. The analyses revealed that the blackish colour is a result of manganese coatings on the grain surfaces and that this feature is regularly found as a border between calcareous and non-calcareous material (see Figure 124). This often goes along with a strong change in pH-values and soluble salts. The process behind this accumulation is most likely a dissolution and precipitation process at the substrate boundary. The sharp boundary is observed in several locations, as explained in the study, mainly related to heuweltjie structures with calcareous materials and along riversides in the lower Koeroegabvlakte where the substrate boundary from calcareous material over lime free material is accompanied by the black layer and can be followed up for several hundred meters. I assume that the calcareous substrate layer is a result of mass movements of former erosion events, caused by irregular, strong precipitation events. The origin of the calcium carbonate is then most likely derived from eroded termite mounds in the upper part of the Koeroegabvlakte. This hypothesis would also explain the relatively small increase in height of the old heuweltjies, which is much stronger in other regions. Further validation by geochronological analyses such as OSL (Optically Stimulated Luminescence) is required.

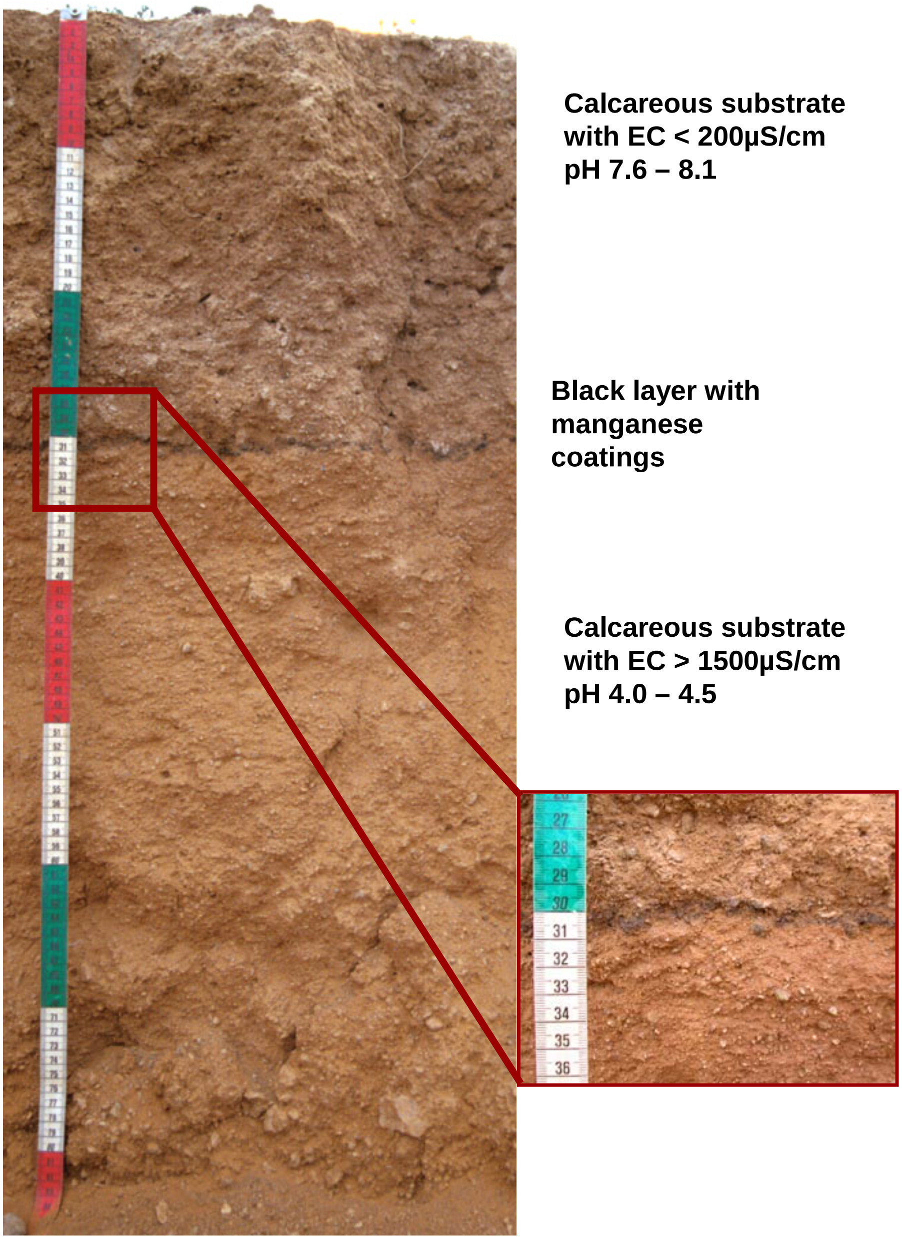


Figure 124 Aspect of the profile 471 in the Richtersveld with typical ‘black layer’ between different substrate layers

3.13 Observatory 20 Numees

3.13.1 Regional overview

The observatory #20 (Numees) is located in the western part of the Richtersveld NP, now part of the Ai-Ais Tranfrontier National Park in the Numees valley (see Figure 112). This valley belongs to the upper catchment of the northwards draining Bloubos rivier. The region has a mean height of 300 – 400 m asl in the plains and up to 800 m at the highest peaks of the surrounding mountains (e.g. the Numees Berg). The geology is a highly complex mixture of sediments of the Gariep Belt and metamorphic rocks of the Namaqua metamorphic complex. All lithological units are affected by thrust faults and are orientated vertically (WILLER 2004). Annual rainfall is around 70 mm with predominantly winter rainfall supplemented by coastal fog during the summer months (JÜRGENS et al. 1999). Prominent feature of the landscape is the mixture of steep slopes, plains and small drainage lines providing a highly diverse range of environmental site conditions.

The vegetation type is the Central Richtersveld Mountain Shrubland (MUCINA & RUTHERFORD 2005), belonging to the Richtersveld bioregion of the Succulent Karoo. It is characterised as a diverse dwarf shrub community with many leaf succulent species. Vegetation of the area has been intensively investigated (e.g. JÜRGENS 1986, 1991, 1999, VON WILLERT et al 1992, GOTZMANN 2002). Research on soil distribution has been carried out by JÄHNIG (1993) and more recently by WILLER (2004) who investigated the influence of lithological units on soil properties. Grazing impact in the area is moderate, depending on the topographic situation. Steep hills are less frequented by livestock and therefore the vegetation dynamics can be regarded as natural. Degradation predominantly occurs in the plains around water points at the western entrance of the park.

3.13.2 Observatory description

The observatory is located approx. 12 km southeast of the Orange River with a coastal distance (Alexanderbay) of 64 km. Compared to the previous observatory situated in a homogenous plain structure, this site is strongly affected by lithological and topographical differences. Figure 125 shows an aerial view of the observatory. The median height is 377 m asl with total differences of 205 m from the western border to the highest mountain peak in the northern centre. Topography is highly diverse with steep slopes in the northern and northeastern part of the observatory while the remaining areas are predominantly hilly structures and dissected plains in allochthon, unsorted substrates. An upper tributary of the Bloubos Rivier is running through the observatory along the gradient from east to west.

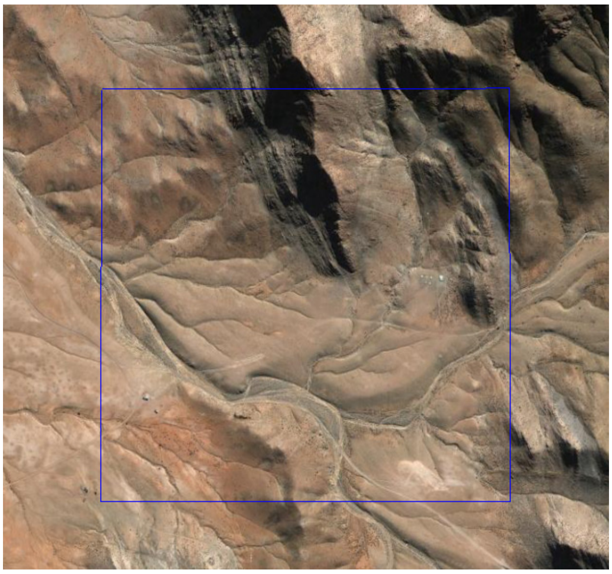


Figure 125 Aerial view of the observatory #20 Numees and surrounding.

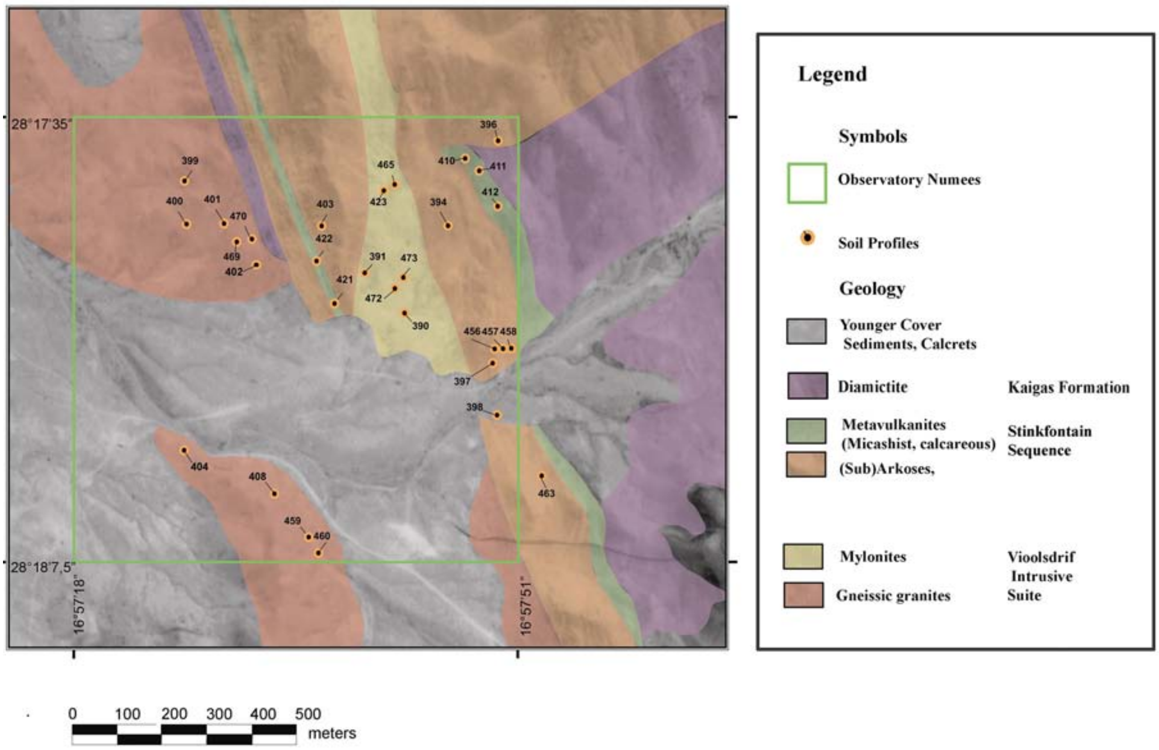


Figure 126 Geology of the observatory #20 Numees with location of selected profiles for lithological analyses (from WILLER 2004)

The geology of the observatory is shown in Figure 126 and described in detail by WILLER (2004). Steep slopes and hilly structures are characterised by shallow substrates while the plains consist of mixed, fragment-rich substrates derived from mass movements, predominantly incorporating calcretes and calcic materials. The southwesterly exposed footslopes and plains are often covered by a silty sand cover, which is often calcareous and predominantly colonised by *Brownanthus pseudoschlichtianus*. Land-use in the area is small stock grazing.

The vegetation is described in detail by JÜRGENS (1986). It comprises mainly succulent members of the *Mesembryanthemaceae, Crassuluaceae, Asteraceae* and *Euphorbiaceae*. For a detailed species list, see also www.biota-africa.org. The observatory has been divided in a total number of nine habitats: highland slopes and medium valleys with a further distinction by exposition and occurrence of rivier elements.

3.13.3 Soils

3.13.3.1 Main soil units

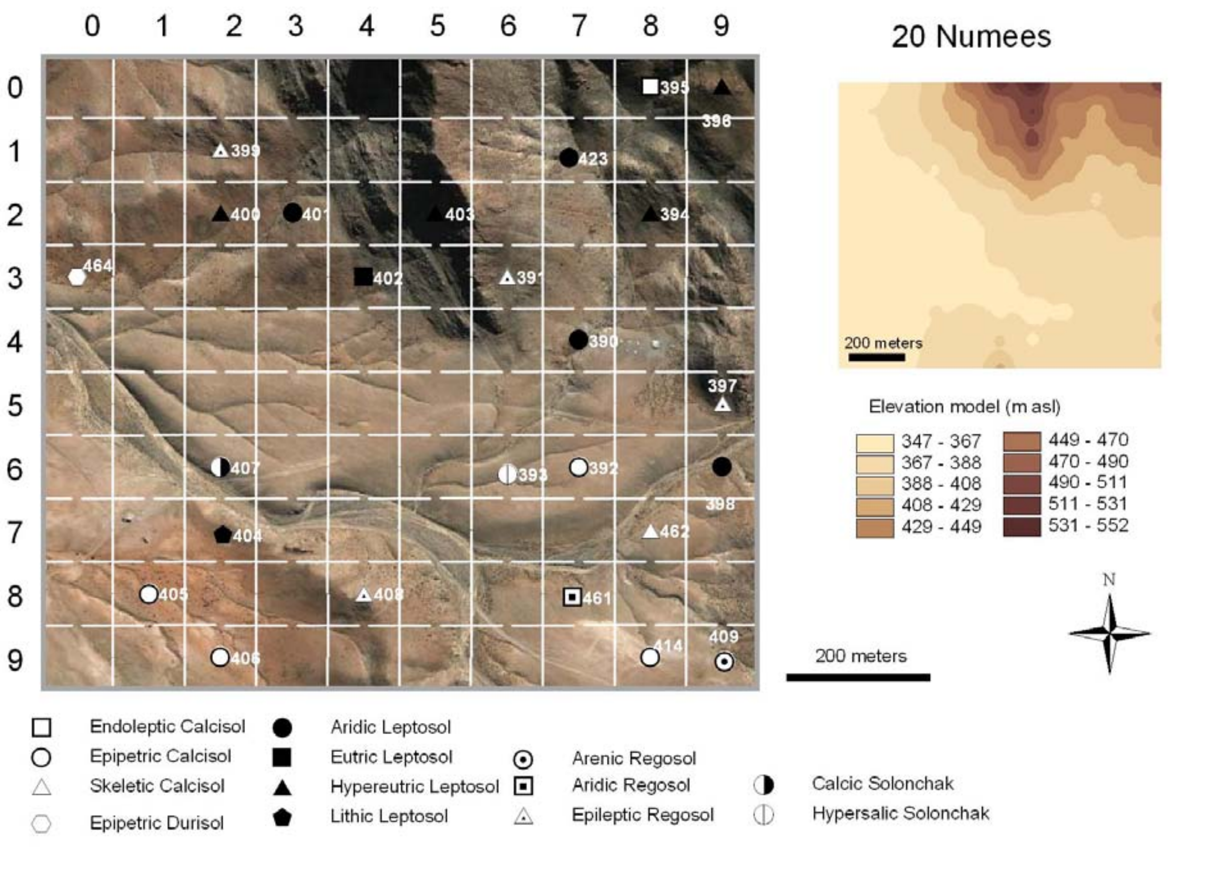


Figure 127 Distribution of soil units (WRB 1998, 1st qualifier level) on the obs. #20 Numees

25 soil profiles were examined according to the standardised ranking procedure. The soil units and their distribution are provided in Figure 127. In Figure 128, the frequency of these soil units on a two-qualifier level is depicted. According to the WRB (1998) Leptosols are the most common group predominantly found on the steeper positions followed by Calcisols and Regosols in the medium valleys and accompanied by the minor occurrence of Solonchaks and Durisols.

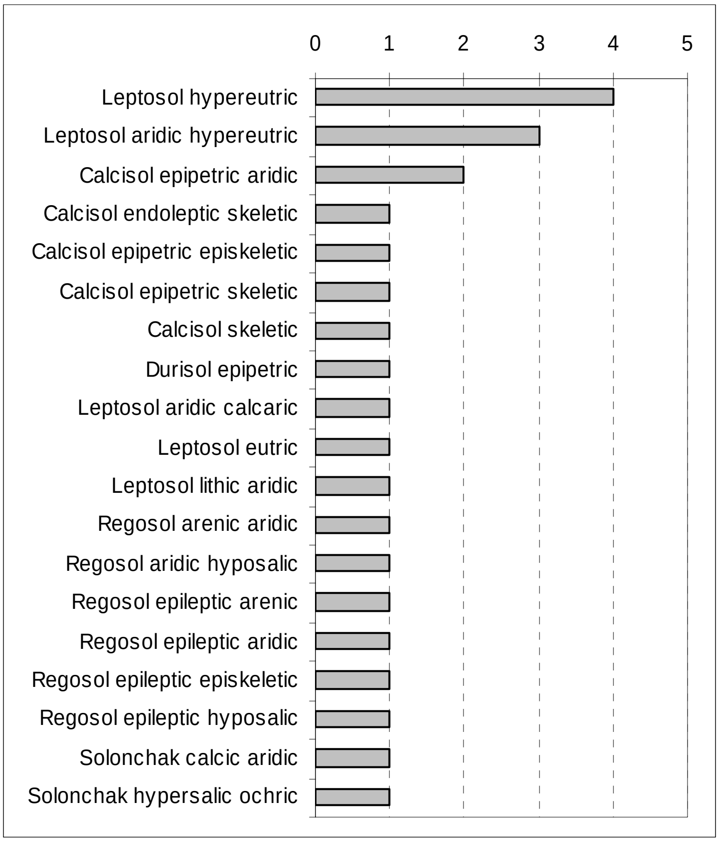


Figure 128 Frequency distribution of WRB (1998, 2nd qualifier level) soil units in obs. #20

3.13.3.2 Remarks on classification

The classification of the soil units is provided in the WRB (1998) nomenclature. The most important features and differences of these soils (limitation by bedrock and coarse fragments, calcic horizon, salinity and base status) could be described sufficiently with the used qualifiers and reference groups. Particularly remarkable is the high number of soil units on the two-qualifier level (19) and even on the first-qualifier level (13).

The application of the new version of the WRB (2006) reveals only minor changes. The frequency of Solonchaks will increase because of the reduced requirements for salic horizons. This enables a more detailed distinction between salt affected and salt free soils.

3.13.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **403**	Ha: **25**	Classification (WRB 1998)	**Hypereutric Leptosol**
		(WRB 2006)	**Haplic Leptosol (hypereutric)**

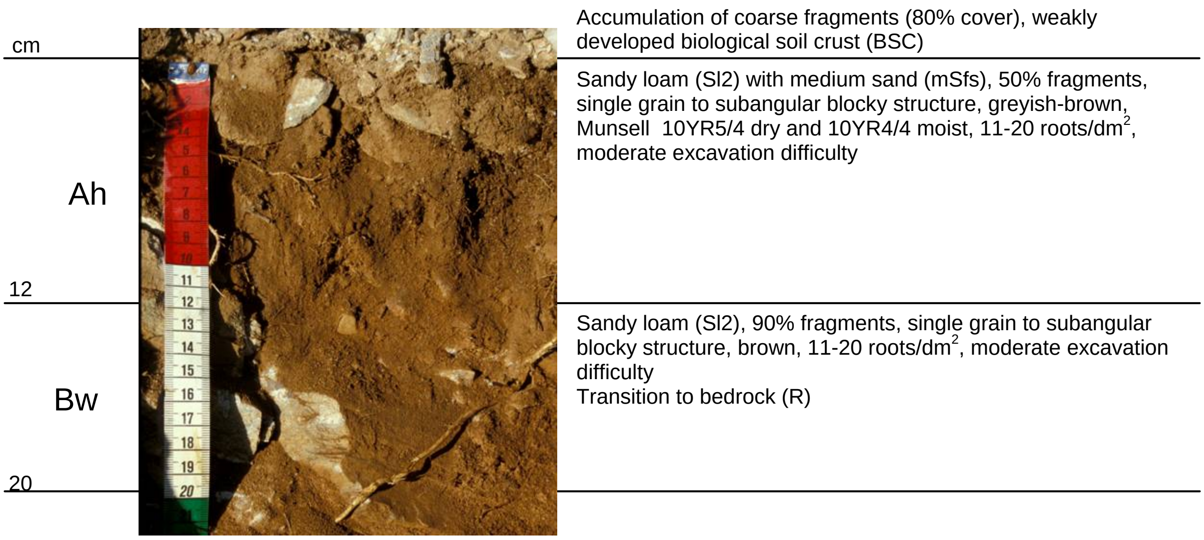


Figure 129 Description of profile 403

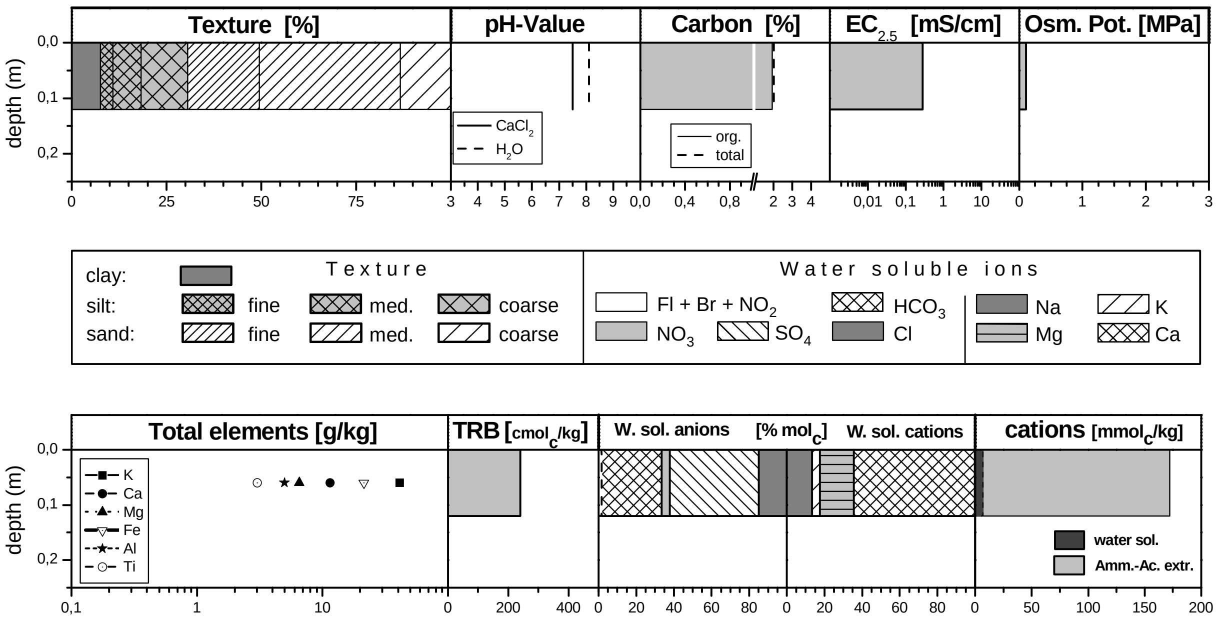


Figure 130 Properties of profile 403

The Hypereutric Leptosol of Figure 129 is a typical example for shallow soils developed on the steep slopes of the observatory. This profile is created on the weathering resistant arkoses of the Stinkfontein Formation. The westerly exposed slope has approx. 60 % inclination. Additionally the bedrock layers have an inclination of 75 % towards the slope, which results in a “flowerpot”-like substrate structure typical for the region, which is one important aspect for the wide range of microhabitats. Run-on of rainwater from surrounding stone cover areas (up to 90 %), variability in depth of the cover layer and root penetration in bedrock fissures and pockets enhances the small-scale heterogeneity of water resources in these systems.

The main texture of the fine earth is loamy medium sand (Sl2) with 30 % of silt and clay. The EC is moderate (280 µS cm^{-1}) and the pH-value is moderately alkaline. Although typically the content of organic carbon increases along the winter rainfall regime of the transect, the values in this profile are comparatively high. This might be a result of the high fine root density in the soil sample. Resulting from the former input of wind-blown material, the total element contents are higher than from the underlying Arkose material, would be suspected with highest values for K and Fe resulting in a mean TRB of 220 $cmol_c$ kg^{-1}. The contents of water-soluble ions are low; the high values in the AM-extractable bases are a result of stronger dissolution processes.

Reference profile # 2

Profile: **407**	Ha: **62**	Classification (WRB 1998)	**Aridi - Calcic Solonchak (Hypersalic)**
		(WRB 2006)	**Calcic Hypersalic Solonchak (Aridic)**

cm	Horizon	Description
		Accumulation of coarse fragments (80%)
8	Ahk	Sandy loam (Su4), 50% fragments, single grain to subangular blocky structure, moderately calcareous, reddish-brown, Munsell 10YR6/6 dry and 7,5YR3/5 moist, 11-20 roots/dm^2, dry, moderate excavation difficulty
25	Bwk	Sandy loam (Su4), 50% fragments, single grain to subangular blocky structure, moderately calcareous, reddish-brown, Munsell 10YR6/4 dry and 7,5YR4/6 moist, 11-20 roots/dm^2, slightly moist, moderate excavation difficulty
45	Bwk2	Sandy loam (Su4), 50% fragments, single grain to subangular blocky structure, moderately calcareous, reddish-brown, Munsell 10YR8/3 dry and 10YR5/4 moist, 11-20 roots/dm^2, slightly moist, moderate excavation difficulty
65	Bwk3	Sandy loam (Su3), 70% fragments, single grain to subangular blocky structure, moderately calcareous, greyish-brown, Munsell 10YR8/2 dry and 10YR5/4 moist, 6-10 roots/dm^2, dry, moderate excavation difficulty

Figure 131 Description of profile 407

Compared to the previous profile, the Aridi-Calcic Solonchak of Figure 131 can be regarded as another extreme of the ranges of typical soil features on this observatory. The profile is situated in a peneplain of deeper allochthon substrates, dissected by some larger run-off rills. The substrate exhibits high contents of calcic materials and a saline character.

The topsoil texture of the profile is silty sand (Su3-4) and like the pH value (8.0), it stays constant over depth. Inorganic carbon is present in all horizons as a component of lime. The $EC_{2.5}$ starts with 250 µS cm^{-1} in the topsoil and increases up to 5 mS cm^{-1} in the subsoil resulting in high OP of 2 MPa. The quotient of $EC_{2.5}$ / EC_5 is around 1.6 in the 3rd and 1.3 in the 4th horizon indicating the presence and an increasing dominance of gypsum with depth.

Except for calcium, the total element contents show a decrease with depth. This is due to the strongly increasing calcium that is bound in lime and gypsum. The high values of the TRB follow the calcium trend. The content of water-soluble ions in the topsoil is low; the enlarged amounts of AM-extractable bases are a result of the dissolution of carbonates and gypsum.

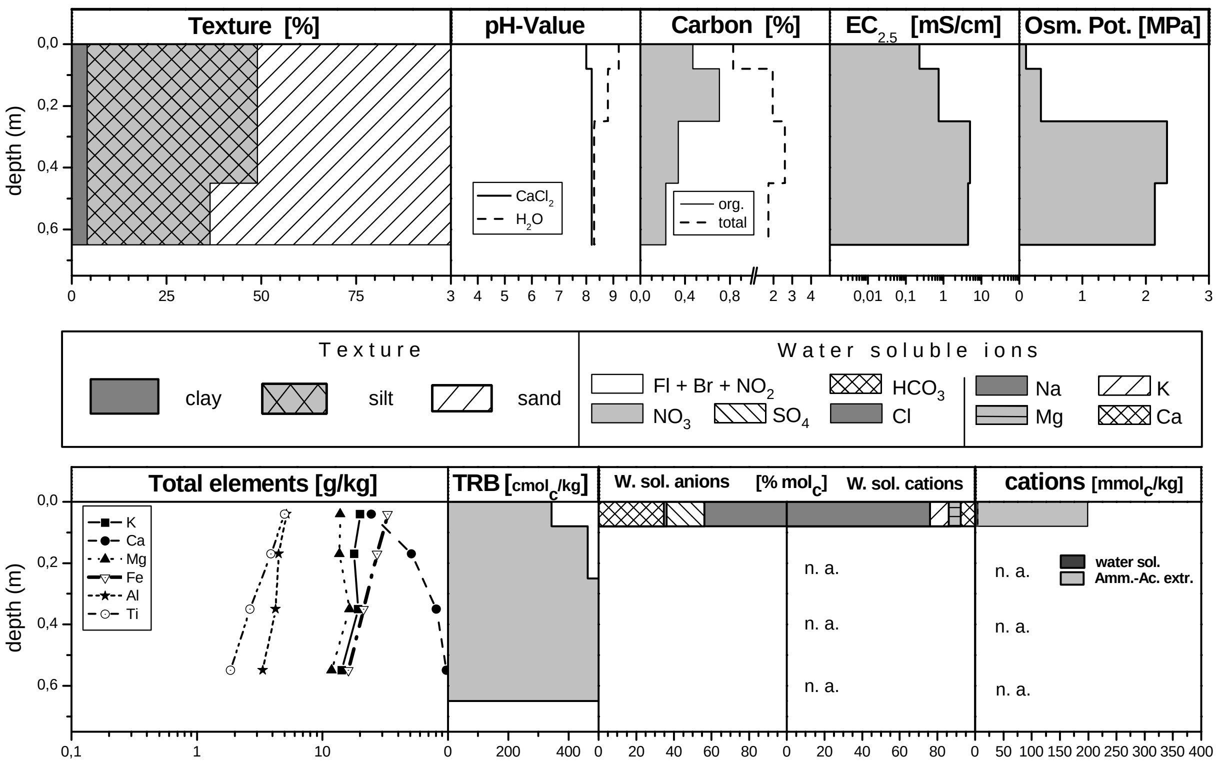


Figure 132 Properties of profile 407

3.13.3.4 Discussion of soil properties

Figure 133 depicts the variability of selected soil properties in three different depth intervals based on data of 25 profiles. The pH-values show relatively wide ranges except for the 3rd depth that is mainly represented by deeper, calcareous soils. The same pattern is evident for the EC, which reaches very high values in the saline Solonchaks. These high values also cause the high EC mean values while the median in the upper horizons represents the non-saline character of the majority of profiles. Within the topsoil layer, the total content of organic carbon is higher and strong variation occurs in all depths. The fine particle percentage (clay & silt) shows similar wide ranges in all depths. This is due to the different parent material ranging from silty sand to sandy silt in the southwest exposed accumulation areas on the footslopes. The variability of the rooting space (RS), caused by different depths of the bedrock, and contents of coarse fragments is moderate. The RS-median of 15 % underlines the shallow, rocky character of the soils.

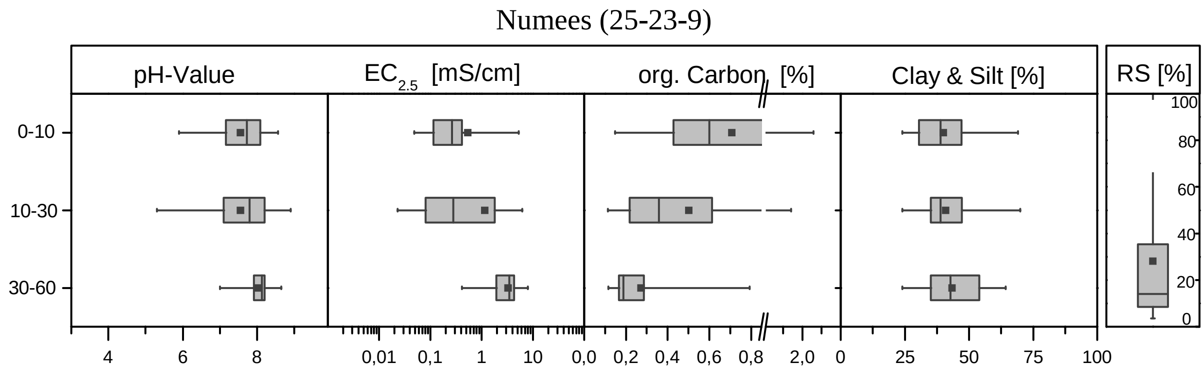


Figure 133 Variability of selected soil properties in three depth intervals for the observatory #20

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

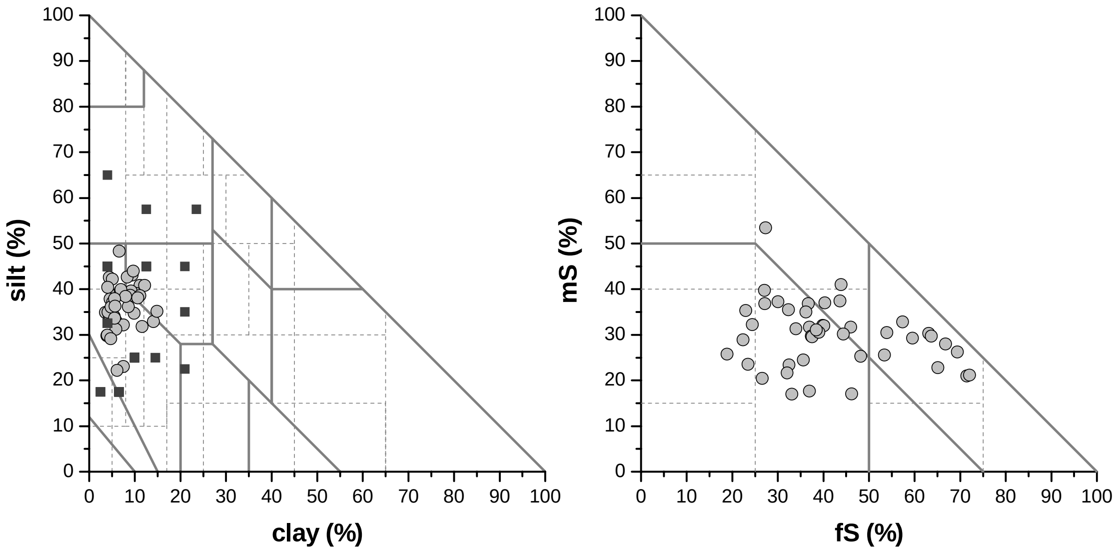


Figure 134 Results of the texture analyses for the observatory #20 Numees

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 134 shows the results of the texture analyses for all samples of the observatory #20. Textures range from silty / loamy sand to sandy silt and silt loam. With regard to the sand fractions, the samples cover a range from coarse sands to fine sands (mSfs, fSms). This uneven distribution is a result of both, different parent materials and weathering behaviour as well as an aeolian input of fine sand. WILLER (2004) showed a strong influence of aeolian sediments (silt & fine sand) in the soils of the region. This has an enormous impact on the differences in geochemical composition (total element contents) of the soils as it reduces the original differences from the bedrock as parent material. However, large differences in the soil units are still evident with respect to their physical properties and dynamic parameters such as salinity, pH-values and nutrient availability.

Pattern analogies in the soil and vegetation distribution are therefore evident on different scales. The most obvious differences exist between the sparsely vegetated saline habitats in allochthon substrates and the surrounding hilly habitats. These are often characterised by one prominent species such as *Ruschia senaria* on the granitic hills, *Zygophyllum prismartocarpum* as a bush form on the calcareous metavulcanites or *Zygophyllum prismartocarpum* as a shrub on the calcareous alluvial sediments (see also JÜRGENS 1986). The steeper slopes represent the next distinction on a habitat scale as heterogeneous 'rock-gardens' with a high number of species. The remarkable occurrence of the same *Zygophyllum* species (*Z. prismartocarpum*) with different growth forms is probably related to the soil physical properties. Both habitats provide a calcareous parent material and comparable soil chemical conditions. The higher growth form on the metavulkanite might therefore be a result of a stronger heterogeneity on the shallower substrate that favours pocket effects in the water storage capacity and availability. The calcareous alluvial sediments on the other hand are more homogenous and thus do not provide such microhabitats. Due to their substrate properties, they still favour the occurrence of *Zygophyllum prismartocarpum*, but in a smaller growth form.

This trend of increasing small-scale heterogeneity from the hilly habitats to the steep slopes causes a strong variability of soil physical site conditions on the steep slopes within a distance of few centimetres. The pattern of soil pockets combined with run-off and run-on effects by exposed bedrock and stone cover provides a wide range of microhabitats with varying water availability. This 'flowerpot' environment enables the remarkably high species richness. Additionally, small-scale changes in the parent material such as calcareous layers in the arkoses amplify the abiotic diversity. Figure 135 shows an example for the strong influence of slight variations in the parent material. In direct vicinity of the permanent monitoring plot (see also JÜRGENS et al. 1999) a micro-transect analysis revealed a pH-gradient from pH 4.8 to pH 9.1 within a distance of 10 m, which is due to low contents of calcium carbonate in the parent material on the western site of the plot. The vertical orientation of bedrocks in the area enhances these effects by a high variation of the sedimentary bedrock units.

Besides the parent material and the small-scale structures, also the exposition and inclination of the slopes influence the vegetation composition. Even slight variations in these factors can result in different temperature regimes and wind exposition resulting in different soil moisture conditions caused by different amounts of rainfall, fog and dew. This is also evident in the weathering of bedrock. Finally, the impact of termites should not be underestimated in the explanation of vegetation patterns. Although not a common feature in this observatory, few remnants of termite mounds (heuweltjies) exist on the slopes. Ants are still active in these structures today. Figure 136 depicts an example of this kind of structure with a prominent vegetation pattern. It is situated on a footslope of a granitic hill with shallow Leptosols and slightly acid, nutrient poor site conditions in the matrix soil. Within a distance of 15 m, strong changes in soil properties occur and analogue the density of the typical species *Ruschia senaria* increases. As no major changes are evident in the soil depth and texture except for positions close to the centre, I assume that the differences in density and vitality of *Ruschia senaria* are caused by the nutrient status.

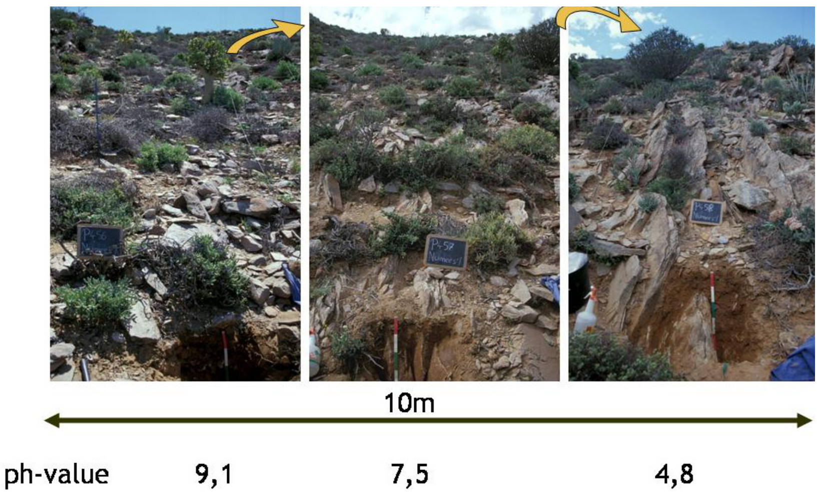


Figure 135 Micro soil transect in direct vicinity of the long term monitoring site Numees

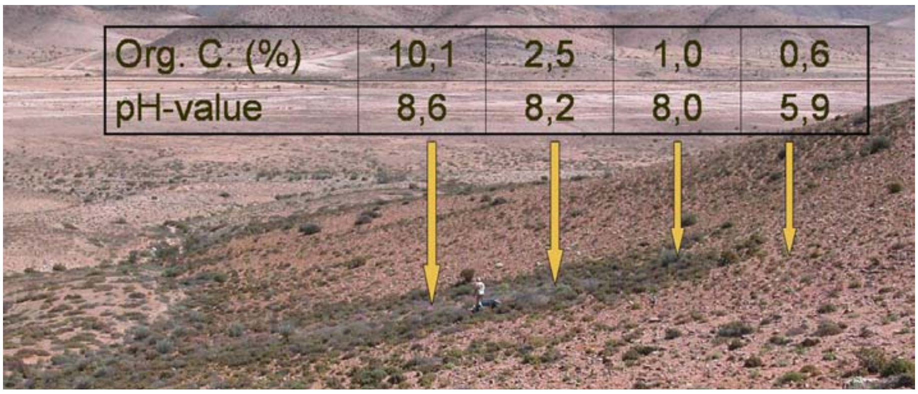
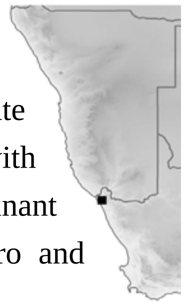


Figure 136 Remnant of a heuweltjie on granitic hills in Numees with result of topsoil analyses

3.14 Observatory 21 Groot Derm / Yellow Dune

3.14.1 Regional overview



The observatory #21 (Groot Derm / Yellow Dune) is located in the coastal area of the western part of the Richtersveld, which belongs to the northern Succulent Karoo and the southern Namib Desert. Dunes of different substrate colour are the major habitat of the region with transition zones to hilly areas with rock outcrops of the Schakalsberge Complex. The main lithology of the dominant Grootderm Formation is different metamorphic rocks such as schist, gabbro and metabasalts (FRIMMEL et al. 2001).

Prominent feature of the landscape is the occurrence of dune sands of marine origin that form different morphologies, which are influenced by the surface of the underlying bedrock. In general, the thickness of the sand layer is increasing to the south. Annual rainfall is around 50 mm with predominantly winter rainfall supplemented by coastal fog during the summer months (DESMET & COWLING 1999).

The vegetation is a dwarf shrub community of the Northern Richtersveld Yellow Duneveld, belonging to the Namaqualand Sandveld bioregion. A detailed description of the vegetation and the pattern of sessile and mobile dunes in the area is provided in DREBER (2005).

3.14.2 Observatory description

The observatory is located approx. 25 km east of Alexanderbay. Compared to the previously described Richtersveld site Numees, the observatory located in a levelled plain structure, is almost completely covered with dune sands. Only few patches that are easily identified by the occurrence of quartzes and rock fragments on the soil surface consist of a shallow sand cover over the bedrock. The median height is 205 m with total differences of 37 m from the northern border to the highest dune parts in the southern part of observatory. The habitats can be categorised as i) dune crests, ii) dune slopes and iii) interdunal valleys.

The vegetation is characterised by mainly dwarf to low growing leaf succulent shrubs such as *Brownanthus pseudoschlichtianus* and *Zygophyllum spp.*. The complete inventory of the vegetation is listed at www.biota-africa.org. A very prominent feature of the area is the occurrence of strong, blackish biological soil crusts, which can cover 100 % of the soil in certain areas. The most obvious differences in site conditions within the observatory are linked to these crusts, which give a dark aspect of the soil surface in contrast to the bright parts with mobile sands. Land-use is characterised by low intensity small stock grazing.

3.14.3 Soils

3.14.3.1 Main soil units

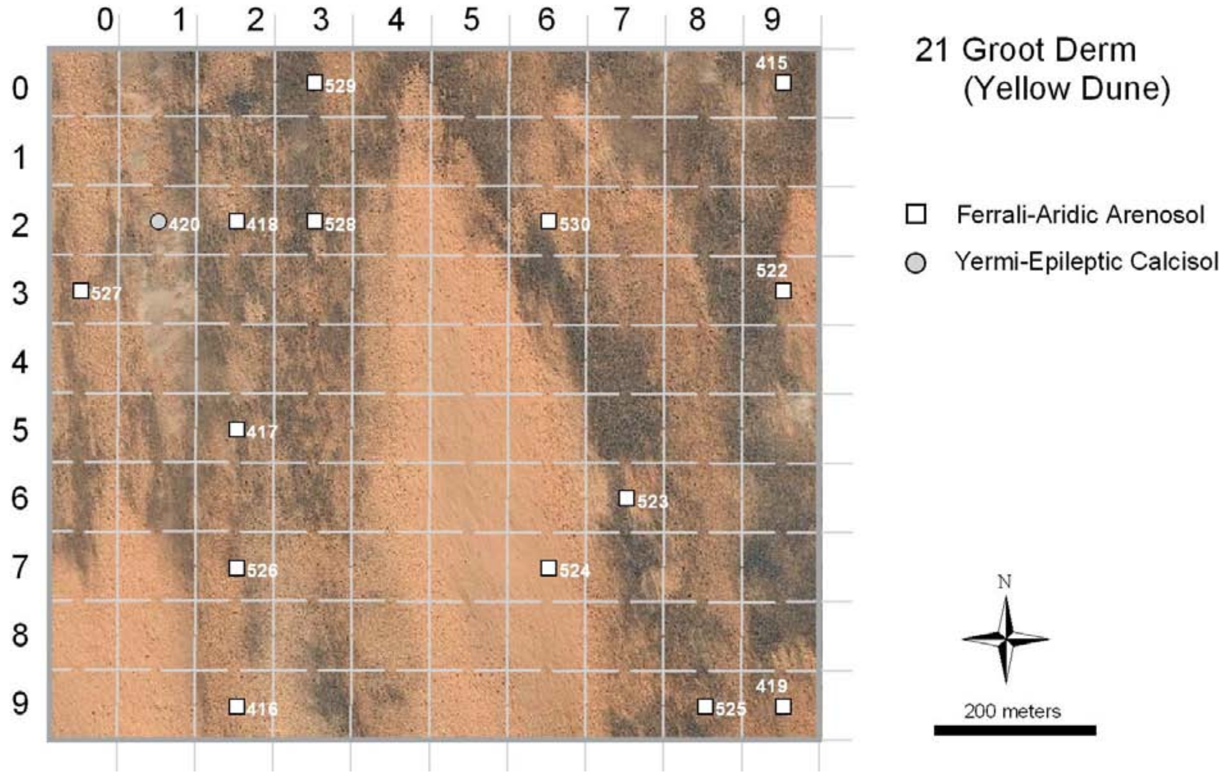


Figure 137 Distribution of soil units (WRB 1998, 2nd qualifier level) on the observatory #21 Groot Derm (Ranking 1-15).

The regional distribution of the soil units of 15 examined profiles is provided in Figure 137. The aerial photograph shows darker areas for sessile dunes with higher vegetation and BSC cover and lighter zones, which are active sand layers with reduced vegetation cover. Light-grey patches in the NW of the observatory represent shallower, calcaric and saline soils. According to the WRB (1998), the soils were classified as one Yermi-Epileptic Calcisol and all of the others as Ferrali-Aridic Arenosols. This distribution strongly expresses the uniform character of the dune system. Only in one position with thin sand cover over the bedrock occurs a Calcisol that is highly enriched in calcium carbonate and salts and characterised by a desert pavement on the soil surface. The development of this profile is in accordance with the low topographical position and the lack of deep drainage prevented by underlying bedrock.

3.14.3.2 Remarks on classification

The classification of the soil units is provided in the WRB (1998) nomenclature, which enables important features of these soils (sandy substrate and nutrient deficiency) to be described sufficiently. However, the prominently developed biocrusts on part of the soils are not detectable in the system, although an important and characterising feature of the soils. The use of the qualifier ‘ferralic’ is debatable due to the alkaline pH-values and median EC values around 200 µS cm^{-1}, which is highly comparable to the Ferralic Arenosols of the observatories #01, #02, #03 and #17. However, ferralic is defined by a low CEC (< 4 $cmol_c$ kg^{-1}), which is characteristic for those sandy soils with low organic carbon content. The CEC is not analysed in this observatory, but AC-exchangeable base was determined. Although the values are higher (6.5 $cmol_c$ kg^{-1}), it was observable that the dominant cation is Ca, which was believed to originate from calcium carbonate dissolution during the extraction procedure. This was indicated by the low and not Ca dominated content of water soluble cations. I decided therefore to use the qualifier ferralic to express the low exchange complex in the substrate.

The application of the new version of the WRB (2006) reveals one important change. Due to the reduced requirements for salic horizons, the EC_e reaches values allowing the use of the qualifier ‘hyposalic’ for some of the Arenosols. This enables a more detailed distinction between more, and less salt affected soils.

3.14.3.3 Description of selected reference profile

Reference profile # 1

Profile: **416**	Ha: **92**	Classification (WRB 1998) (WRB 2006)	**Ferrali-Aridic Arenosol (hypereutric)** **Ferralic Arenosol (Hypereutric, Aridic)**

cm	Horizon	Description
0–10	A	Recent accumulation of Fine Sand (fSms), single grain structure, light brown, Munsell 10YR6/6 dry and 10YR5/4 moist, 3-5 roots/dm^2, low excavation difficulty
10–20	Ah	Buried Ah-horizon with Fine Sand (fSms), single grain structure, greyish-light brown, Munsell 10YR6/6 dry and 10YR4/4 moist, 21-50 roots/dm^2, low excavation difficulty
20–35	Bw	Fine Sand (fSms), single grain structure, light brown, Munsell 10YR6/6 dry and 10YR4/4 moist, 11-20 roots/dm^2, low excavation difficulty
35–70	Bw1	Fine Sand (fSms), single grain structure, light brown, Munsell 10YR6/6 dry and 10YR4/4 moist, 6-10 roots/dm^2, low excavation difficulty
70–90	Bw2	Fine Sand (fSms), single grain structure, light brown, Munsell 10YR6/6 dry and 10YR4/4 moist, 1-2 roots/dm^2, low excavation difficulty

Figure 138 Description of profile 416

The Ferrali-Aridic Arenosol of Figure 138 is a typical example for the soils developed in pure dune sands of the observatory Groot Derm. The profile is situated close to a shrub and thus affected by recent accumulation of wind blown sand (phytogenic mound). The upper layer of 10 cm covers a buried Ah-horizon, which is clearly detectable through the higher number of roots and also higher content of organic carbon. Additionally, the top layer shows clear signs of layered accumulation of wind-blown sands. The main texture of the profile is medium sand (mS) with only small amounts of fine sand. Compared to other profiles, the characteristic biocrust (see Figure 142) is not evident due to the burial of the former soil surface and ongoing sedimentation dynamics.

The EC of around 100 µS cm^{-1} is nearly constant with depth whereas the pH-values show some differences, especially between the recent accumulation and the former Ah-horizon. The total element contents are increasing with depth from the Ah-horizon onwards, indicating some shifts in mineral composition of the sands. As mentioned in the remarks on soil classification, the Ac-extractable cations are fairly high, but most likely a result of dissolution of calcium carbonate during the extraction procedure.

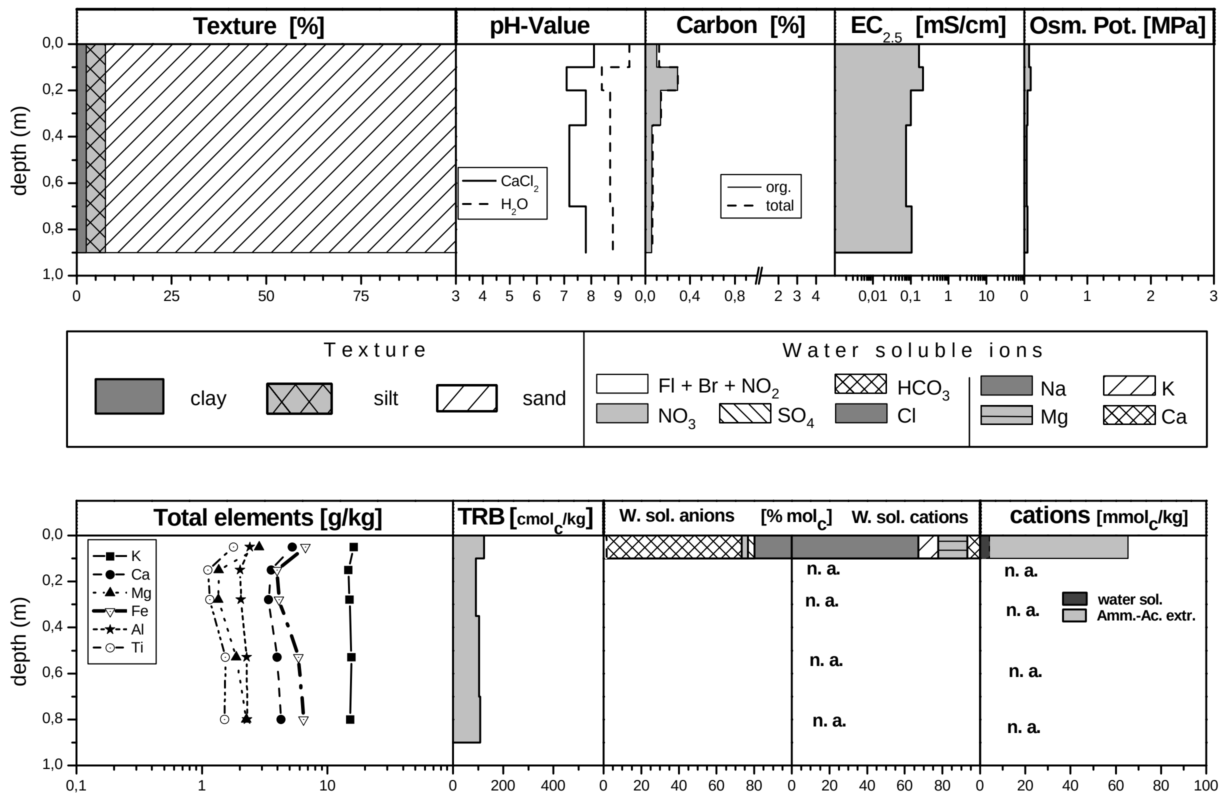


Figure 139 Properties of profile 416

3.14.3.4 Discussion of soil properties

Figure 140 depicts the variability of selected soil properties in three different depth intervals based on data of 15 topsoil samples and 6 profiles. The pH-values show a relatively small range from neutral to moderately alkaline conditions and no substantial variation with depth. EC show wider ranges in the upper horizons, which include the shallower, salt accumulated sites and decreased variation in the deepest layer. Organic carbon shows a similar pattern with relatively wide ranges in both topsoil layers caused by variations in the age of the substrate and the coverage of biological soil crusts. The fine particle percentage (clay & silt) shows no range except for one outlier caused by the Calcisol with loamier substrates. The rooting space is only limited at few interdune positions by the underlying bedrock.

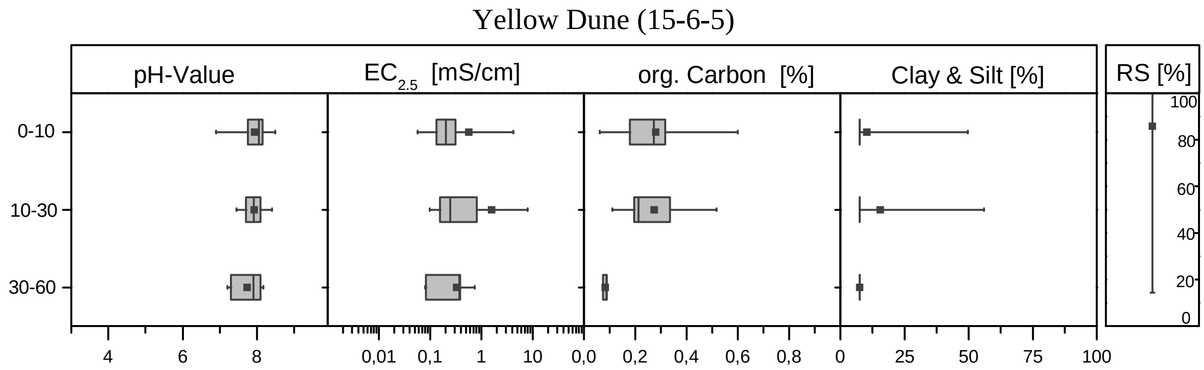


Figure 140 Variability of selected soil properties in three depth intervals for the observatory #21

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

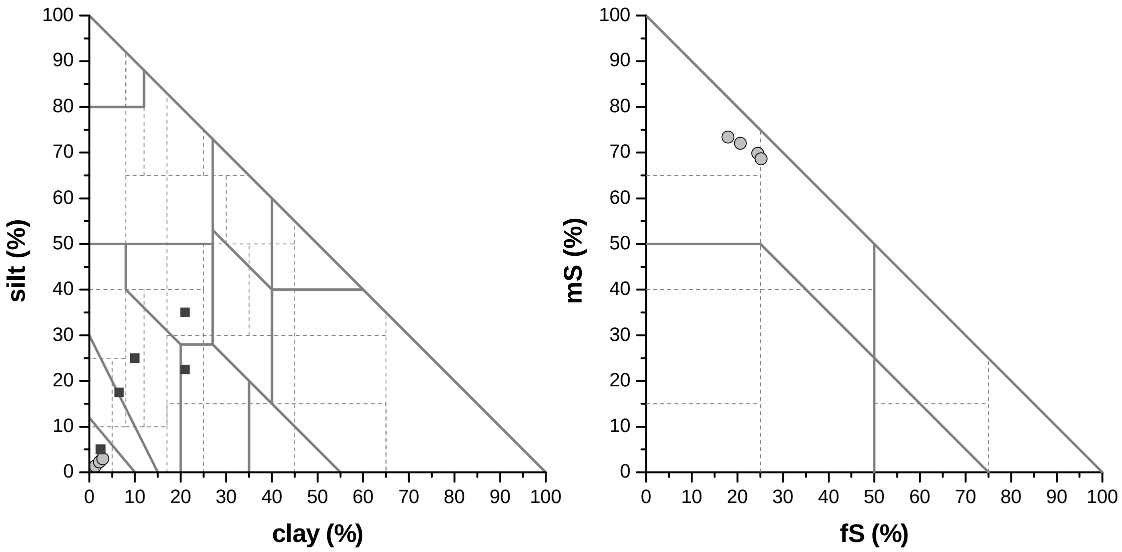


Figure 141 Results of the texture analyses for the observatory #21 Groot Derm

Squares = finger test (all samples) and circles = lab analyses (selected samples)

As typical for its origin, the texture (Figure 141) is pure sand with nearly no silt and clay percentage. The dune sands are predominantly (around 70 %) medium sands (mS) with few contingents (< 5 %) of coarse sand. Only for the schist-derived material of the Calcisols loamy textures were found.

Figure 142 Examples of the strongly developed biological soil crust on the observatory #21

Pattern analogies in the soil and vegetation distribution on the observatory are evident in the distinction of the salt affected Calcisol as a special microhabitat, which comprises different species or a bare aspect, and the Arenosols as the matrix soils. Within these matrix soils, a distinction between the *Stoeberia beetzii* - *Brownanthus pseudoschlichtianus* community on the sessile dune elements with strongly developed BSCs and the *Lampranthus hoerleinianus* - *Ruschia sarmentosa* community on the habitats with shifting sands and low BSC cover (DREBER 2005) becomes visible. The occurrence of the prominent BSC cannot be related to analysed soil properties and seems to be affected by topography, which drives the pattern of shifting sand areas. Another feature of the dune sand soils is the shallow rooting depth, mainly restricted to the first 20 cm of soil, which is regarded as a morphological characteristic of Succulent Karoo shrubs (ESLER & RUNDEL 1999) with their adaptation to low, but quite regular rainfall events.

3.15 Observatory 22 Soebatsfontein / Quaggasfontein

3.15.1 Regional overview

The observatory #22 (Soebatsfontein) is located with a costal distance of approx. 30 km in the central Namaqualand between the coastal plains and the escarpment of the Kamiesberg area (see Figure 143). The village Soebatsfontein belongs to the Kamiesberg municipality in the Northern Cape Province.

The site is part of the Namaqualand Hardeveld with gneissic hills and low-lying valleys and shows transitions to the sandveld bioregion towards the coast (DESMET 2007). Geologically, the region belongs to the Namaqualand Metamorphic Complex with igneous rocks such as gneisses and granites of the Little Namaqualand suite (WATKEYS 1999). The topography is undulated with mean heights between 200 m asl in the plains and 500 m asl on the rocky outcrops. In general, height is increasing towards the eastern Kamiesberg region. Mean annual rainfall is around 150 mm and occurs mainly as highly predictable winter rainfall (DESMET 2007). Additional moisture is provided by coastal fog and dew.

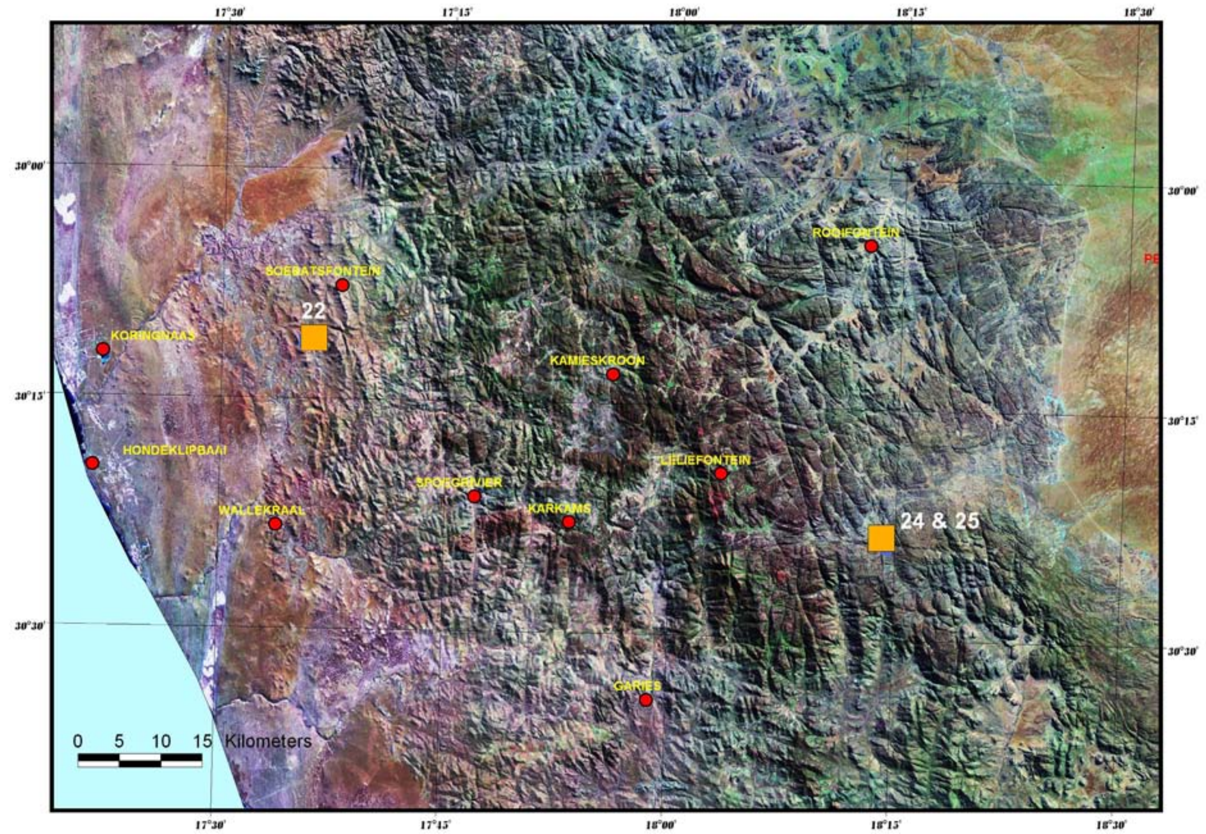


Figure 143 Satellite view of the central Namaqualand incl. the location of the observatories #22 Soebatsfontein and #24 / #25 Leliefontein / Remhoogte (Landsat TM © Nasa)

This section of the Namaqualand, the Lowland Succulent Karoo, is part of the Namaqualand-Namib Domain (JÜRGENS 1991). The vegetation is characterised by species-rich dwarf shrub communities of mainly leaf succulent species and only few grasses. It is one of the most important biodiversity hotspots of the world (MYERS et al. 2000). A detailed overview is provided in DEAN & MILTON (1999).

A prominent feature of the landscape consists of the rounded, slightly elevated, sparsely or distinctly, compared to the matrix,vegetated spots of up to 35 m diameter and 1.5 m in height called 'heuweltjies' (meaning 'small mounds'). The occurrence of these mounds is widely spread over the coastal and lower escarpment zone of the Namaqualand and their coverage can reach values of 25 % of the landscape (ELLIS 2002). The density of heuweltjies ranges from two to six mounds per hectare (PICKER et al. 2007). Due to their particular physical and chemical soil properties and the accompanying disturbance effects, the heuweltjies bear distinct vegetation compared to the vegetation on matrix soils. Depending on rainfall regime and grazing pressure, this led to a regular pattern clearly visible in the landscape (see Figure 144). Whereas in the more arid parts these structures often remain barer than the surroundings due to water stress, the regions towards the Cape are often characterised by heuweltjies as fertile islands with more favourable conditions for plant growth compared to the matrix.

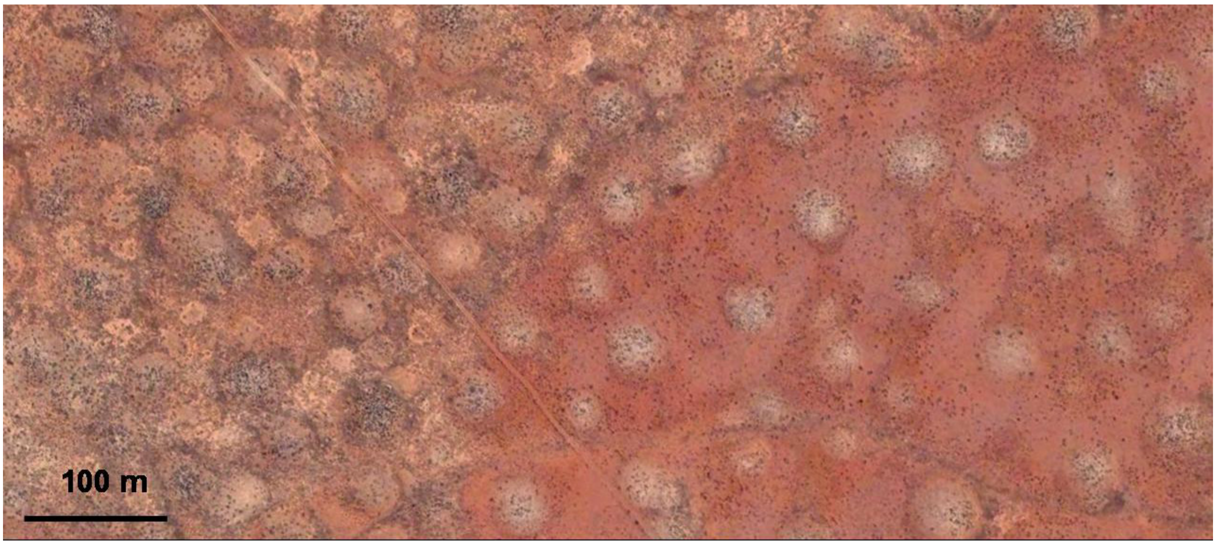


Figure 144 Example of Heuweltjie pattern in the landscape near Soebatsfontein

Until now, the origin of the heuweltjies is not fully understood. A wide range of theories has been published (e.g. LOVEGROVE & SIEGFRIED 1986, 1989 for a review; MOORE & PICKER 1991), but similar to the 'fairy rings' in Namibia (VAN ROOYEN et al. 2004), which can be regarded as the northern continuation of the heuweltjie area, no convincing general explanation has been published to date. Older theories speak of geogenic (limestone faults by VAN DER MERWE 1940; dorbank erosion by SLABBER 1945) or climatic and biogenic origin of the mounds (e.g. TEN CATE 1966). LOVEGROVE & SIEGFRIED (1989) show evidence that it is most likely the combination of termite activities and burrowing small mammals, such as the mole rat, that created the structures. Further studies regarding dating of the frequent calcium carbonates in the mounds corroborate the theory that the mounds are relictic (MOORE & PICKER 1991) and even date them back to the last glacial maximum 20,000 years BP (MIDGLEY et al. 2002). ELLIS (2002) concentrates his studies on the formation of hardpans (calcic and duric horizons) in the heuweltjie soils and also addresses the climatic impact on the soil conditions within the mounds. He strengthens the termite origin theory by relating hardpan formation to specific silica translocation processes and assumes a relictic formation based on the recognition that mounds are only features of old land surfaces. The most recent publication (PICKER et al. 2007) corroborates the theory that heuweltjies are old but still active termite mounds of *Microhodotermes viator*, a harvester termite that is associated with low winter rainfall and specific vegetation, similar to the spatial distribution of the heuweltjies.

With regard to ecology, the heuweltjies are a highly interesting feature as they strongly increase the pedodiversity of the region and therefore pose a key element in the vegetation structure. One of the most astonishing features is the presence of calcium carbonate in a landscape dominated by acid igneous rocks. It is assumed a result of biogenic precipitation caused by the enrichment of Ca by decomposed plant material and hydrogen carbon (MONGER 2002).

With regard to vegetation science, the pattern assigned to soil conditions is a striking feature and important for the high species turnover rates on a small scale. This actual pattern aside, DESMET (2007) raises an interesting hypothesis as he sees a relationship between the occurrence of heuweltjies and the phylogenetic history of the region. Today land-use often creates degraded patches due to overgrazing or abandoned fields, which are frequently colonised by disturbance-adapted plant species such as *Galenia africana*. Surprisingly, the majority of these disturbance-adapted species are endemic to the regional flora which is a hint towards a long evolutionary history of these species in the region. DESMET (2007) assumes that the heuweltjies are most likely the ancient disturbance sites in the ecosystem rather than the impact of large mammals.

Today, the predominant land-use in the area is small stock farming. Occasionally, rain-fed crop production occurs on the plains, but many of the marginal locations were abandoned and became invaded by indigenous shrubs (HOFFMAN & ROHDE 2007). The traditional grazing system in the Soebatsfontein area was formerly pastoral followed by a fenced commercial farm of ‘De Beers Mining Company’. Since 1998, the community of Soebatsfontein re-owns the utilisation right for 15,000 ha land.

3.15.2 Observatory description

The observatory is located approx. 10 km south of the Soebatsfontein village with a coastal distance of 29 km. The topography is undulated with slopes of different inclination and valley structures with more levelled character. The site is dominated by a gneissic outcrop area stretching from the northwest to the central south of the observatory. Except for a small area in the southwest, the slopes have an eastern exposition and the heights differ from 260 to 440 m asl (see Figure 145).

The upper slopes typically have a heterogeneous surface structure characterised by boulders and bare surfaces of the gneissic bedrocks. This structure favours down boulder positions with additional water supply by run-off / run-on processes and are dominated by larger shrubs and small trees. Valleys and lower slopes with a lower heterogeneity are characterised by creeping or smaller leaf succulent shrubs such as *Cephallophylum inequale* (ANDERSON et al. 2004). Here, the most differentiating factors are the heuweltjies, which show distinct soil conditions compared to the matrix. In the southeastern section, there is a small quartz dominated habitat .

Mean annual rainfall is around 120 mm with maxima from May to September (BIOTA weather data 2001-2006). Fog and dew provide additional water supply for the shallow rooting perennial plants. The observatory is dissected by small, shallow drainage lines, i.e. gullies and other erosion features (see HOYER 2004). The main drainage line ends in an allochthon fan structure in the northeastern part of the observatory. Here, the heuweltjies are barely visible from the ground, only the aerial photograph reveals the presence of heuweltjies, which are nearly completely covered with younger sediments. Only the ancient tops of the heuweltjies remain visible mainly because of their distinct vegetation and lighter substrate colour, but they are not higher than their surroundings anymore.

Due to the importance of topography, four habitat types were distinguished as i) westerly exposed valley and lower slope, ii) easterly exposed valley and lower slopes, iii) plain or saddle in upper parts, and iv) steeper slopes dominated by outcrops and boulders. Recent studies of the observatory analysed the phytodiversity along the topographical gradient (TENE KWETCHE SOP 2004) and the soil variability according to erosion potential and processes (HOYER 2004).

3.15.3 Soils

3.15.3.1 Main soil units

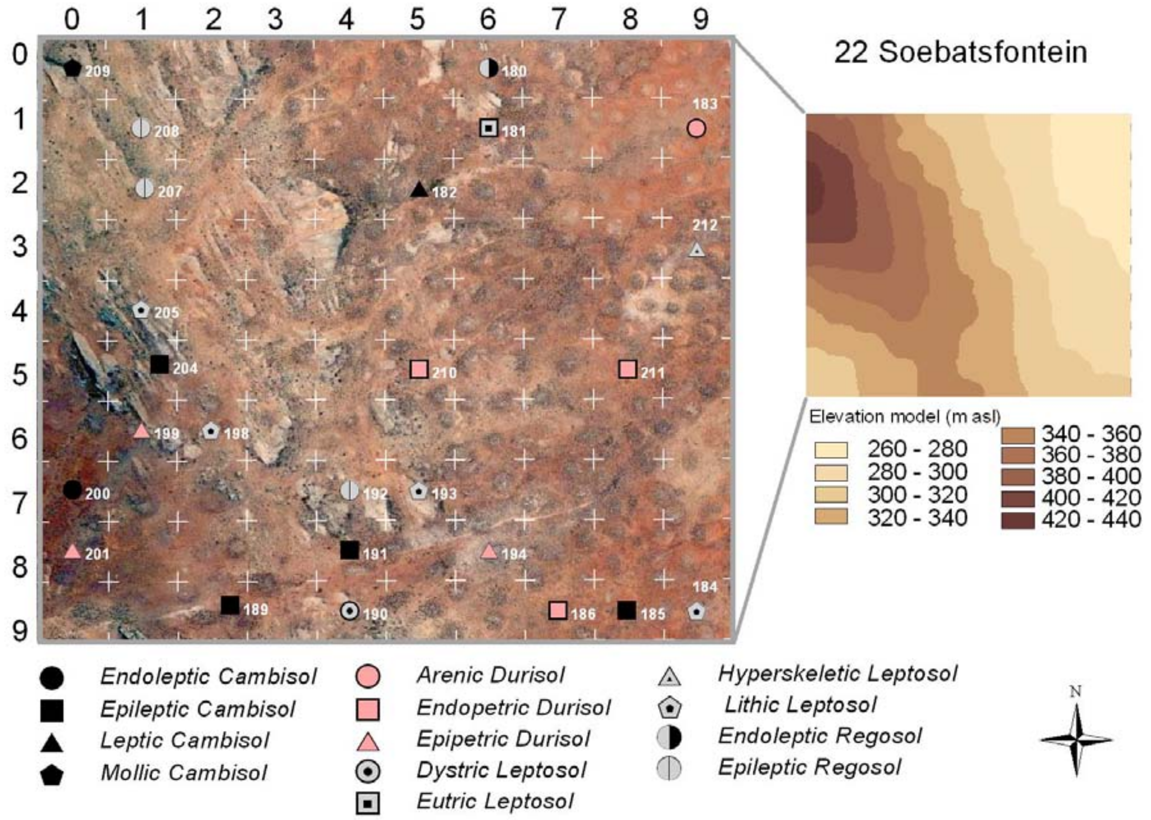


Figure 145 Distribution of soil units (WRB 1998, 1st qualifier level) on the observatory #22

For 25 soils of the observatory #22 (Soebatsfontein), the soil units and their regional and frequency distribution are provided in Figure 145 and Figure 146. Based on a two-qualifier level of the WRB (1998) system, the classification results in 19 different soil units, predominantly Durisols and Cambisols. Durisols are exclusively associated with the occurrence of heuweltjies, while Cambisols are mainly found in the lower valleys in between the heuweltjies on deeper substrates. For these soil units, properties depend on the depth of duripan, bedrock and the content of coarse fragments. A unique feature and not typical for this climate is the Mollic Cambisol that has developed below an exposed bedrock and that receives both, run-on water and debris and nutrients by a weathering of the rock surface that is intensively colonised by lichens. These site conditions led to a path intensively colonised with soil organisms, which created a diagnostic ‘mollic’ topsoil. Leptosols and Regosols mainly occur on the higher positions, but the lower valley also includes areas with shallow bedrock, as the Leptsols in the eastern part indicate. In general, the soils are characterised by bedrock contact within the first meter indicated by different ‘leptic’ qualifiers except for the accumulation area in the north-eastern section of the observatory.

Additional transect studies for the detailed analyses of small-scale soil variability revealed further soil units, which are not included in the frequency distribution depicted. High enrichment of soluble salts and calcium carbonate, occurring at some locations on the heuweltjies and qualify for the soil units Solonchak and Calcisol. This demonstrates the enormous role of the heuweltjies for pedodiversity. In an additional study (HERPEL, in prep.) the importance of small-scale variation in soil properties is investigated.

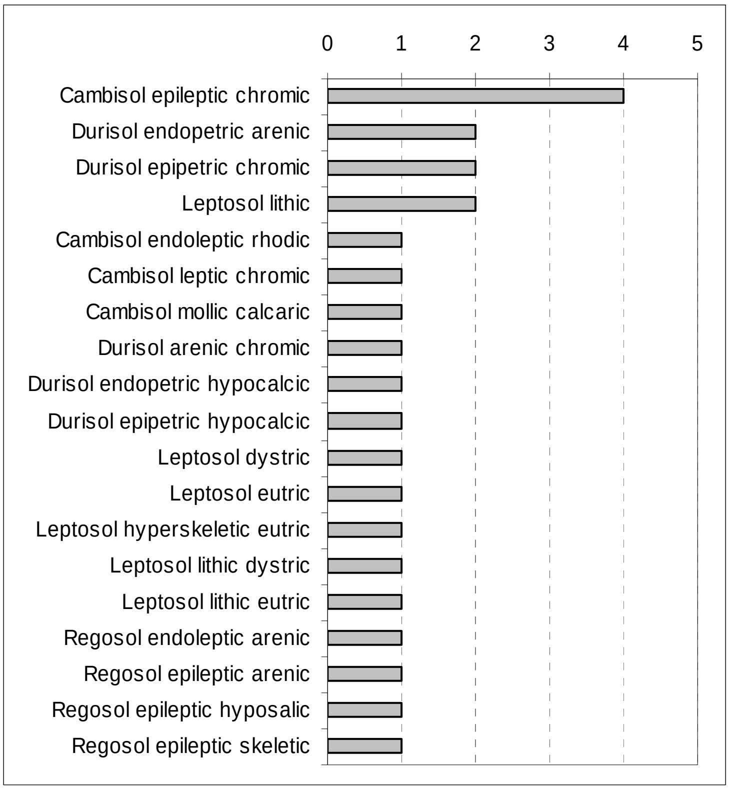


Figure 146 Frequency distribution of WRB (1998, 2nd qualifier level) soil units in observatory #22

3.15.3.2 Remarks on classification

Most of the important characteristics of soils (depth of bedrock and crusts, texture, duric horizons, calcium carbonate content, pH and base status) could be described sufficiently with the applied qualifiers and reference groups. On the other hand, the degree of salinity is not describable with the WRB (only hyposalic in Regosols), although this is an additional important feature of the heuweltjies. The use of the qualifier ‘mollic’ in an arid environment with igneous rock as parent material seems strange. However, diagnostic properties were fulfilled and the qualifier provides the most detailed description of the properties.

The application of the new version of the WRB (2006) reveals major changes. The newly introduced definitions for the salic horizon now allows expressing the salinity by choice of Solonchaks for profiles which formerly had to be classified as Durisols or Cambisols without the option to i) use a 'salic' qualifier and ii) reach the requirement for Solonchaks. A further development is the qualifier 'nudilithic' which separates exposed bedrock from very shallow Leptosols. In summary, the new version facilitates a more precise description of the main soil features in this observatory and emphasises its to some extent salty features.

3.15.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **186**	Ha: **97**	Classification (WRB 1998)	**Hypocalci-Endopetric Durisol (Chromic)**
		(WRB 2006)	**Hypocalcic Duric Hypersalic Solonchak**

cm	Horizon	Description
0–15	Ah	Sandy Loam (Su3) with medium sand (mSfs), 1% fragments, subangular blocky structure, reddish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 21-50 roots/dm^2, dry, low excavation difficulty
15–30	Bwk	Sandy Loam (Su3) with medium sand (mSfs), 1% fragments, subangular blocky structure, slightly calcareous, reddish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 21-50 roots/dm^2, dry, moderate excavation difficulty
30–65	Bwk2	Sandy Loam (Su3) with medium sand (mSfs), massive, slightly cemented structure, extremely calcareous, reddish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 21-50 roots/dm^2, slightly moist, moderate excavation difficulty
65–80	Bwkq	Sandy Loam (Su3) with medium sand (mSfs), massive, slightly cemented structure, extremely calcareous, reddish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, slightly moist, moderate excavation difficulty, durinodes (10 %)
80–85	Bwq	Sandy Loam (Ls4), reddish-greyish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, moderate excavation difficulty, durinodes (20 %)
85–90	Bqm	Duripan (massive) Munsell 7,5YR5/6 dry and 5YR4/6 moist, high excavation difficulty

Figure 147 Description of profile 186

The Hypocalci-Endopetric Durisol of Figure 147 is an example for the heuweltjies' soils . Typically, the substrates are free of coarse bedrock fragments but inhabit varying amounts of fine gravel and durinodes and fragments of broken duripans. In this profile, fragments occur only in the transition zone to the massive silcrete amounts of 10 – 20 %. The texture of the profile is sandy loam with equal shares of medium and fine sand and a mean bulk density of 1.45 cm^{-3}.

The pH-value is neutral to moderately alkaline and the EC is high with values around 4 mS cm^{-1} in the subsoil resulting in a high OP of 1-2 MPa (calculated). Organic carbon shows a typical decrease with depth whereas higher values of inorganic carbon in the subsoil indicate an increasing calcareous character until a depth of 80 cm. In the underlying duric horizon the soil is non-calcareous.

The total element contents are constant with depth except for Ca that follows the calcareous trend. Mg and Fe decrease in the durinode horizon. TRB are high, mainly caused by Ca and K. Water soluble ions are characterised by Na and Cl reaching values of 100 $mmol_c\ kg^{-1}$ in the subsoil. The exceptionally high values of AM-extractable ions are a result of a strong dissolving process of powdery $CaCO_3$ during the extraction procedure.

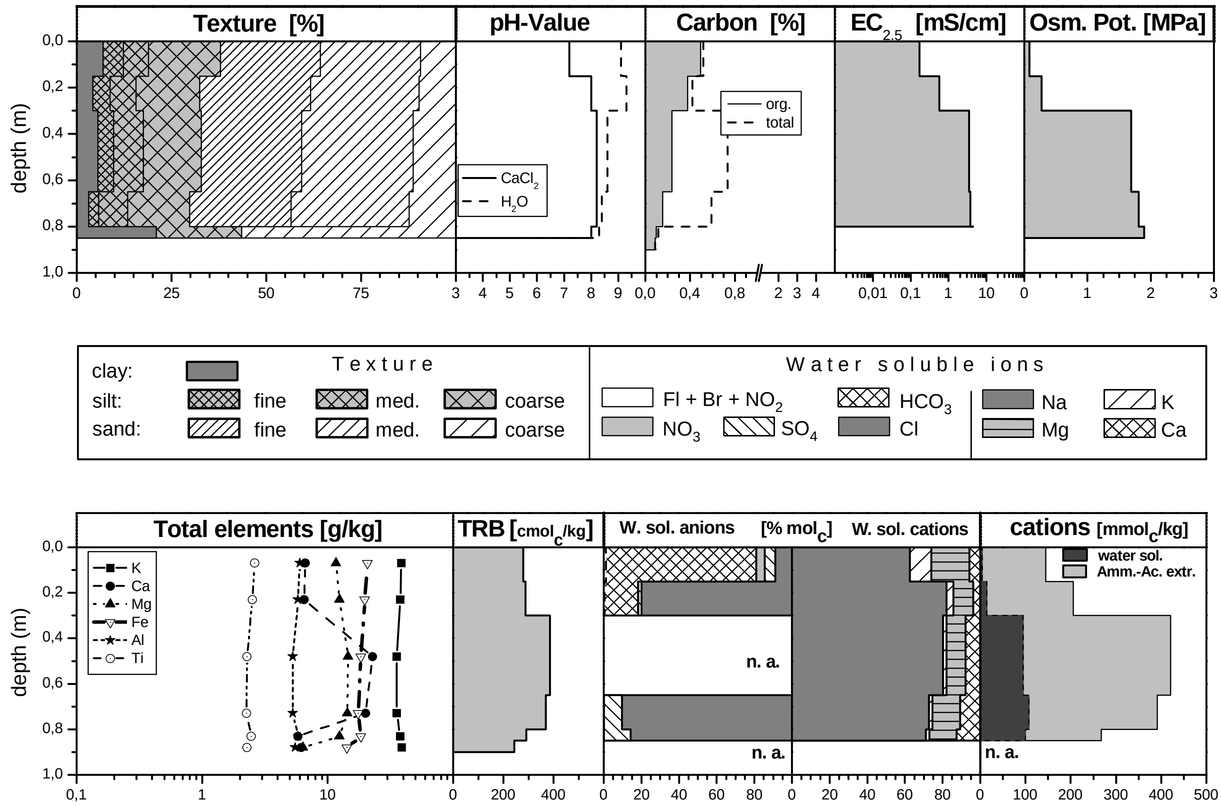


Figure 148 Properties of profile 186

Reference profile # 2

Profile: **210**	Ha: **55**	Classification (WRB 1998)	**Areni-Endopetric Durisol (Chromic Dystric)**
		(WRB 2006)	**Endopetric Durisol (Arenic, Chromic)**

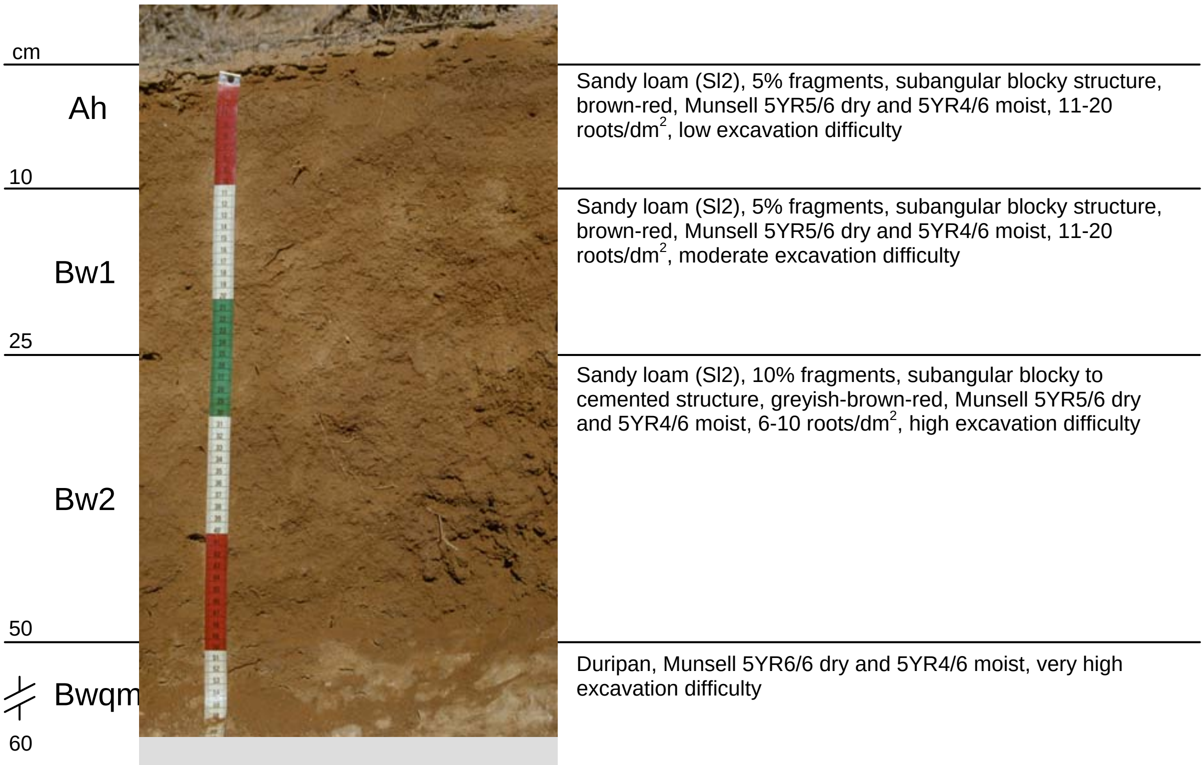


Figure 149 Description of profile 210

The Endopetric Durisol of Figure 149 is a typical example for the soils in immediate vicinity of the heuweltjies, which go along with a massive concentric shaped duripan. In areas with a high heuweltjie density, these soils form the matrix soils, whereas in areas with greater distances between the mounds Cambisols without cementations occur frequently. In general, soil properties are similar to those Cambisols, but the main feature, the cemented duric horizon, restricts the rooting depth and can occur in shallow depth positions.

This non-calcareous profile shows a duripan as a massive, bedrock-similar cementation below the depth of 50 cm. The main texture of the upper horizon is sandy loam (Sl2) with a lower percentage of silt compared to the previous profile and a mean bulk density of 1.65 cm^{-3}. Field tests show no texture change compared to the duripan, which indicates an induration within the profile. The pH-value is neutral in the top and in the subsoil with a marked decrease in the second horizon. $EC_{2.5}$ is much lower than in the heuweltjies (80 to 300 µS cm^{-1}) and organic carbon shows a typical decrease with depth. The total element contents are constant with depth except for Mg, which increases with depth. The amounts of water-soluble and AM-extractable ions are comparatively low.

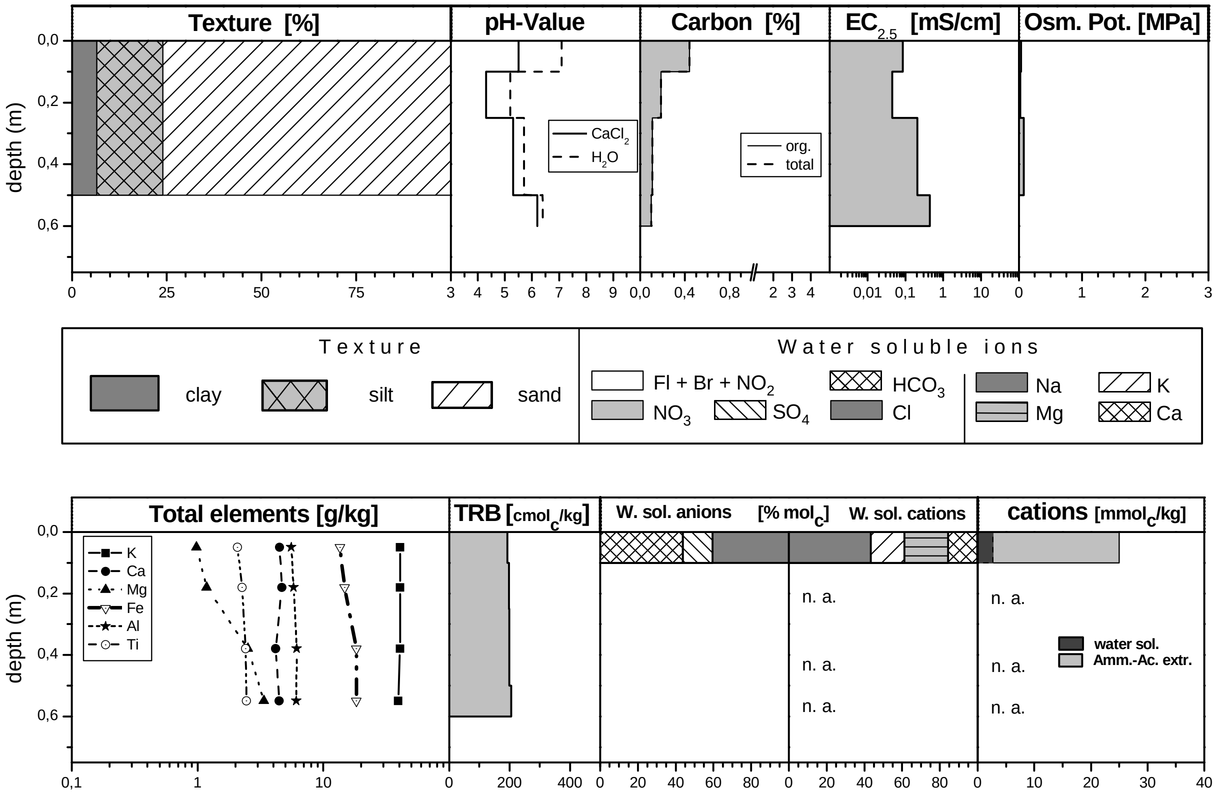


Figure 150 Properties of profile 210

Reference profile # 3

Profile: **190**	Ha: **94**	Classification (WRB 1998)	**Dystric Leptosol**
		(WRB 2006)	**Haplic Leptosol (Dystric)**

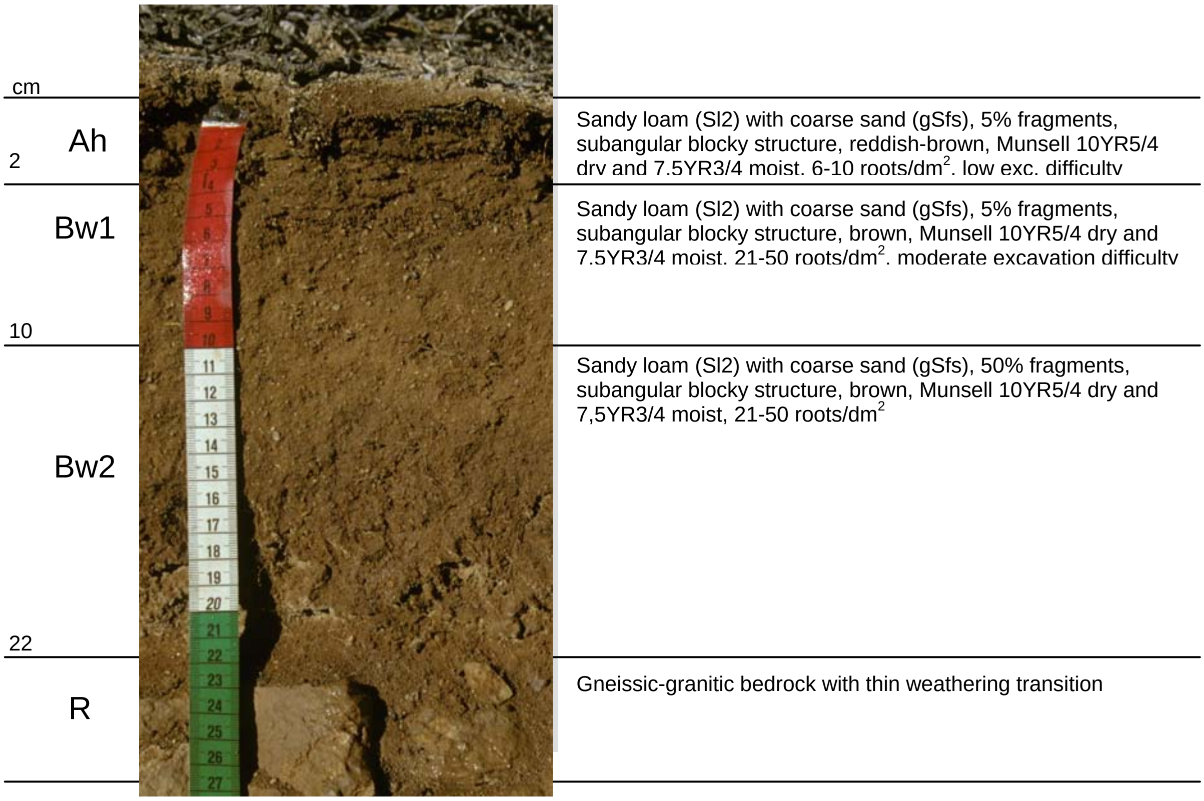


Figure 151 Description of profile 190

With Dystric Leptosol (Figure 151), a soil unit mainly occurring in the steeper slopes and bedrock dominated habitats, the range of typical soils in Soebatsfontein is complete. In this example, the gneissic-granitic bedrock in a depth of 22 cm shows only few signs of weathering and is not penetrable by roots. The texture of this non-calcareous profile is sandy loam (Sl2) with a higher percentage of coarse sand compared to the previous profiles. The pH-values decrease strongly from slightly acid in the topsoil to very strongly acid in the third horizon. $EC_{2.5}$ reaches moderate values of 100- 700 µS cm^{-1} and organic carbon is relatively high with values of 0.6 -1.1 %. The total element contents are constant with depth and water-soluble ions and AM-extractable ions are relatively low.

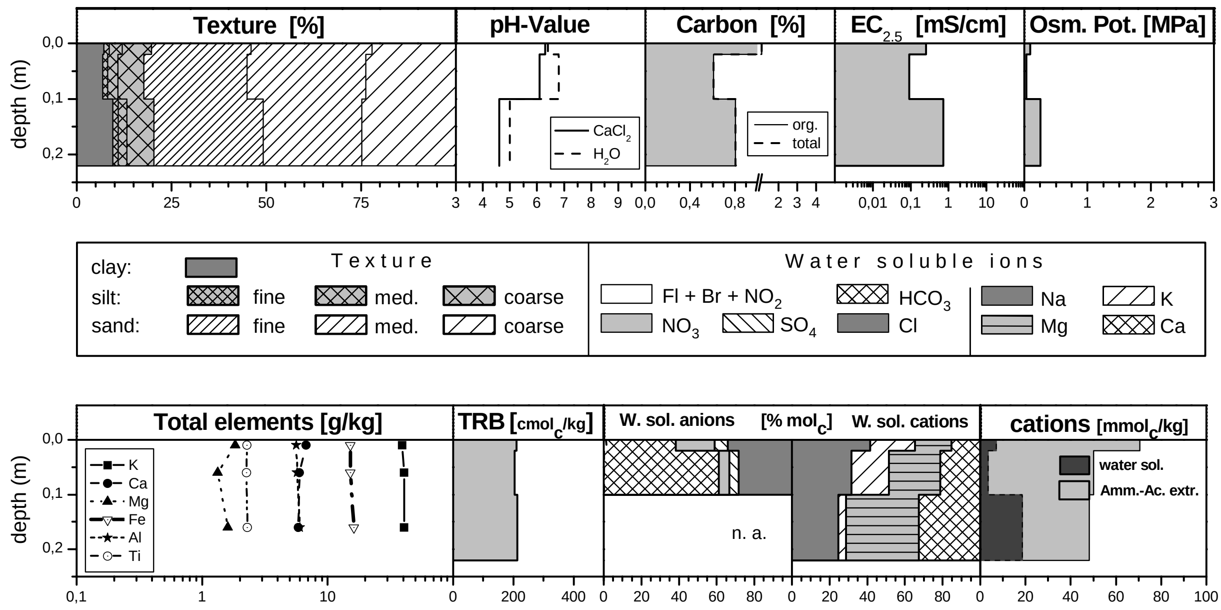


Figure 152 Properties of profile 190

3.15.3.4 Discussion of soil properties

Figure 153 depicts the variability of selected soil properties in three different depth intervals based on the data of 25 profiles. The pH-values show a wide range and variation with depths, mainly characterised by a decrease in the second horizon. This is a typical feature for the observatory. $EC_{2.5}$ covers wide ranges from low to high salinity with median values around 200 µS cm^{-1}. A high variability combined with a clear decreasing trend with depth is observable in organic carbon reflecting the varying amounts of humus accumulation, which is due to different site conditions, i.e. varying water supply. The fine particle percentage (clay & silt) shows narrower boxes with no variation in depth indicating a rather similar substrate except for the heuweltjie site with higher silt contents. The median rooting space (RS) represents the overall shallow and rocky character of the area, but deep profiles as well as extremely shallow sites also cause the wide range of rooting space. In general, the high variability of soil properties is indicated by both, the total range in parameters and the wide boxes indicating an even distribution of these different site properties.

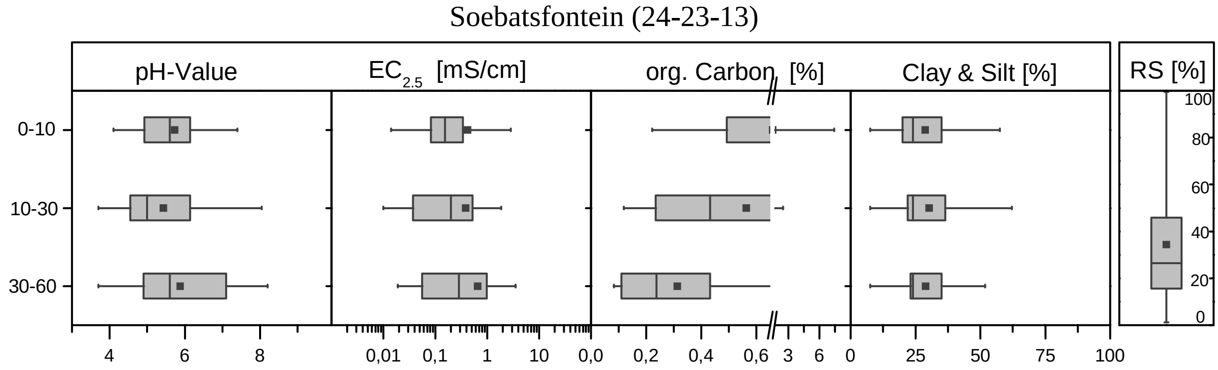


Figure 153 Variability of selected soil properties in three depth intervals for the observatory #22

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

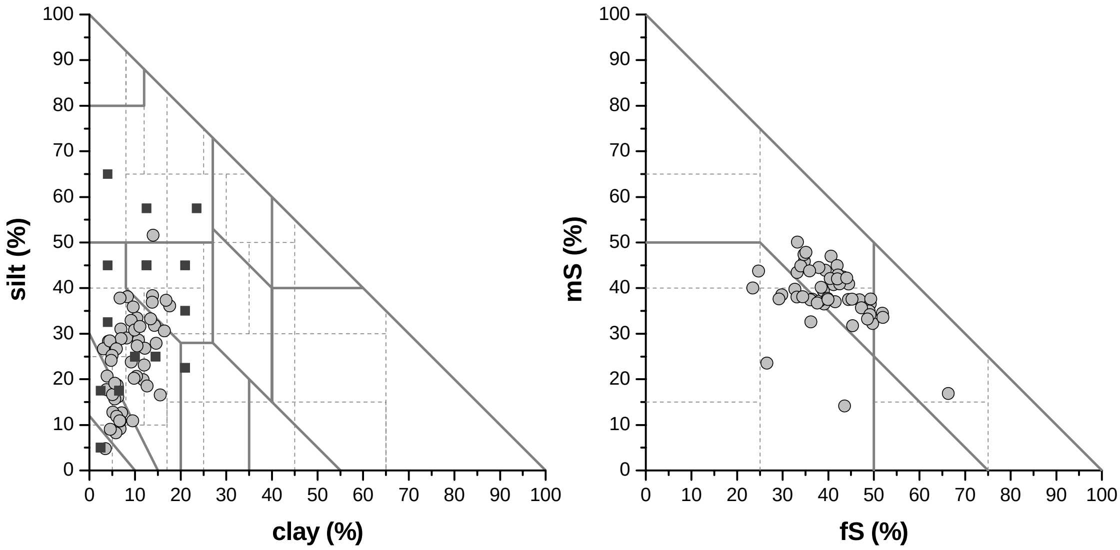


Figure 154 Results of the texture analyses for observatory #22 Soebatsfontein

Squares = finger test (all samples) and circles = lab analyses (selected samples)

The texture (Figure 154) ranges from sand to silt loam with the finest textures occurring in the heuweltjies while pure sands occur in the topsoils of the allochthon structure of the 'alluvial fan' in the northeast of the observatory. With regard to the sand fractions, the samples can be regarded as one cluster with few outliers. Samples with the lowest content of coarse sand originate from the heuweltjies. In contrast, the matrix soils of the heuweltjies veld and the Leptosols of the outcrop areas show a higher coarse sand content while the relation of the medium to fine sand fractions remains comparable. Thus, a basic comparability of the substrates is given for the observatory, only affected by i) higher coarse sand contents in horizons above bedrock and ii) probably by a reduction of coarse sand in the construction process of heuweltjies. In order to verify this hypothesis, further analyses with focus on sand fractions are required. Such analyses have to take into account even slight cementation of fine particles by silica, which can affect the sieving results of sand fractions.

Pattern analogies in the soil and vegetation distribution are evident on different scales. On a broader scale, a clear analogy in topography, soil conditions and vegetation in the observatory is visible through a shift towards higher diversity and different species in the heterogeneous boulder habitats with a high range of environmental site conditions (see TENE KWETCHE SOP 2004). On a small scale, very distinct differences in the soil and vegetation distribution are evident for the heuweltjies and the surrounding matrix. Concentric patterns of both, soil properties and plant species distribution are clearly visible in the field and are a result of soil chemical properties as well soil physical effects caused by duripans.

The very different soil conditions on a small scale were additionally investigated by means of a transect across a heuweltjie. The results are provided in Tab. 5 and Figure 155. All profiles within and in the direct vicinity of the mound are heavily affected by the occurrence of durinodes in the centre and massive duripans outside the heuweltjie. A general trend of high values in the centre to lower values outside is evident for silt, pH, $CaCO_3$, EC, and total element contents such as Ca, Mg, but also Mn, Fe, and others. It is important to note that the increase in elements is much higher than the increase in silt. Therefore the differences in element content cannot be a result of textural changes between the microhabitats. Additionally, highly soluble salts such as NaCl are strongly enriched in the mound and cause EC_e values up to 40 mS cm^{-1} resulting in high osmotic potentials, which increase water stress for the plants.

Tab. 5 Analyses of a microtransect with five profiles across a heuweltjie structure in the observatory #22. Results are means of all horizons in each profile

HEUWELTJIE SOEBATSFONTEIN

Parameter	Unit	Matrix	Slope	Centre	Slope	Matrix	Median of region
distance	m	18	8	0	-8	-20	
Clay	%	11.7	11.2	9.7	10.8	12.2	n.a.
Silt	%	22.5	27.0	30.1	30.9	17.8	n.a.
Sand	%	65.7	61.8	58.9	58.4	69.7	n.a.
pH ($CaCl_2$)	pH	5.6	7.7	8.1	8.1	5.1	6.0
$CaCO_3$	%	0.0	0.2	1.5	3.2	0.0	<0.1
EC_e	mS/cm	17.5	7.4	40.0	26.6	1.2	2.3
Ca	g/kg	3.2	5.6	20.7	14.1	3.9	4.5
Mg	g/kg	3.2	6.6	10.3	12.3	2.2	1.7
Crusts	-	Duripan	Durinodes	Durinodes	Durinodes	Duripan	-

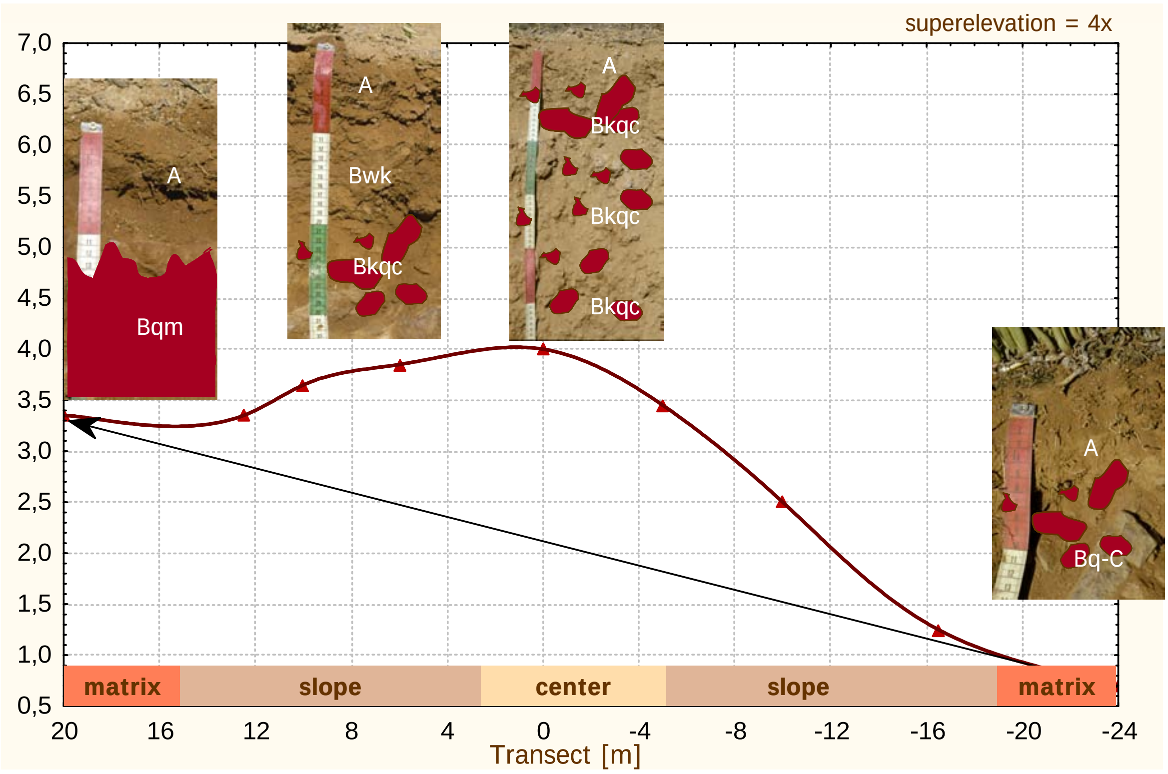


Figure 155 Scheme of the heuweltjie transect in Soebatsfontein with typical soil units and duripans

As typical for heuweltjies in arid landscapes, the centre is enriched in calcium carbonate, which can reach values up to 15 %. This would qualify for a Calcisol according to the WRB. Requirements for a salic horizon are also met by many heuweltjie profiles resulting in a classification as a Solonchak, a saline soil that is typically restricted to flat landscapes with a salinity input by dust or water.

Heuweltjies are undoubtedly a fascinating feature and of high importance for the pedo- and biodiversity of the area. The processes behind these physical and chemical accumulations of material and their shaping of the entire landscape are still under discussion (see above). It is not possible to discuss this topic conclusively in the context of this study, however, in the following I will interpret my results briefly according to the recent discussion in literature. Independent of whether the mounds are ancient or recent heritage, it is widely accepted that they originate from termite activity (PICKER et al. 2007) and probably accompanying processes, which are not identified or understood to date. The studies of ELLIS (2002, overview) corroborated the termite theory by explaining the occurrence and the formation of hardpans (calcrete and silcrete) in the heuweltjies. The central process must be the decomposition of organic material, which can - under arid or semi arid conditions - result in an enrichment of elements derived from decomposed plant material. This also includes silica in form of bio-opal from the plant tissue. Precipitation of biogenic calcium and magnesium carbonate (see MONGER 2002 for an explanation) together with the accumulation of salts raises the ph-values into strongly alkaline dimensions. Under these conditions, the biogenic silica becomes dissoluted and can thus be translocated with water, reaching from the centre into the depth and/or towards the margins of the mounds. Due to drying processes and a lower pH-value, precipitation of silica occurs and forms durinodes and crusts.

The results of this study corroborate ELLIS' (2002) theory, finding massive constructions of hardpans and an enrichment of elements, which have to be caused by an ongoing input and decomposition of plant material over long periods. The pH-values reach dimensions described for the dissolution of bio-opal. This is also true for the transect study in the Koeroegabvlakte which revealed a similar pattern. The recent study of PICKER et al. (2007) emphasises an ongoing activity of *Microhodotermes viator* as the ancient and recent key process for the formation of heuweltjies. This would be coherent with finding very old calcretes (MIDGLEY et al. 2002), but raises other questions:

i) The correlation between mean annual rainfall and the density of mounds by PICKER (2007) is not solely an indication of the actual activity of *Microhodotermes viator*; it can be also a relictic correlation based on the same rainfall pattern but with different total precipitation amounts.

ii) During our studies, termite activity was occasionally observed in the mounds, but we never observed any material accumulating processes on the soil surface, which could be an indication of ongoing mound creation.

One explanation might be the high number of burrows in the mounds caused by aardvarks (*Orycteropus afer*), which is probably responsible for material accumulation in case of absence of mound building termites. With respect to the older theories, which state wind accumulation as an important factor, it needs to be stated that although higher silt contents are present in the mounds, the grain size distribution does not indicate any aeolian processes. Finally, the regular pattern of the heuweltjies indicates a persistence of mound location for long periods. This is evident by the results of the soil survey where no signs of old mound locations were found in between the present structures.

Today, many heuweltjies on the observatory show signs of erosion on the easterly exposed flanks. In combination with other erosion features (see HOYER 2004), this indicates an actual erosion, which is the main threat for soil resources in the region. Over-utilisation over the past decades is assumed to be one reason for the increase in erosion phenomena. Resting the camps and low stocking rates are the current strategies to deal with these problems. However, productivity is low and, with respect to global change scenarios, it can be expected to decrease even further (see MACKELLAR et al. 2007, RICHARDSON et al. 2007). Maintaining the soil resources as the key ecological element will be even more difficult with a changing rainfall regime. This refers particularly not to the overall amount of precipitation, but to the expected intensity of single rain events with an increasing percentage of summer rainfall in the area.

3.16 Observatories 24 (Leliefontein/Paulshoek) & 25 (Remhoogte)

3.16.1 Regional overview

The observatories #24 (Leliefontein/Paulshoek) and #25 (Remhoogte) are located approx. 100 km east of the coast and 40 km southeast of Kamieskroon close to the village Paulshoek in the Leliefontein communal area, which belongs to the Kamiesberg Municipality. The area is located in the Kamiesberg area, an escarpment between the low-lying costal plains and the Bushmanlandplateau in the east (see Figure 143).

The Kamiesberg area is located in the central Namaqualand and is characterised by granite massifs and landscapes with rolling dome-shaped hills and almost flat filled valleys in between (DESMET 2007). Geologically, the region belongs to the Namaqualand Metamorphic Complex with igneous rocks such as gneisses and granites of the Okiep Group (Garies subgroup) (WATKEYS 1999). The topography is undulated with mean heights between 800 m asl in the valleys and up to 1700 m asl on the domes of the Kamiesberg. In general, mean height east of the Kamiesberg (approx. 1000 m asl) is only slightly increasing towards the eastern Bushmanland Region which again decreases in height towards the Kalahari basin. Rain falls with an annual mean of around 150 to 250 mm with higher values up to 400 mm in some westerly exposed mountains and precipitates mainly as highly predictable winter rainfall (variation coefficient 33 %) (TODD & HOFFMAN 1999, DESMET 2007). Further to the east, the proportion of summer rainfall increases strongly within a short distance of approx. 50 km and drives the bushmanland ecotone.

The study area is part of the Bioregion Namaqua Hardeveld with the vegetation types Namaqualand Blomveld and the Eastern Klipkoppe shrubland (MUCINA & RUTHERFORD 2005, ANDERSON & HOFFMAN 2007). The vegetation is characterised by leaf succulent species in the valleys and plains, while the hills and rocky outcrops show higher proportions of non-succulent shrubs. Trees are rare and restricted to watercourses. As typical for the winter rainfall regime, only few grasses occur (TODD & HOFFMANN 1999). The area belongs to an important biodiversity hotspot of the world (MYERS et al. 2000). A detailed overview is provided in DEAN & MILTON (1999).

Predominant land-use in the area today is small stock farming. On the plains, rain fed crop production (wheat, oats, barley, and rye) occurs in both, communal areas and on private farms. The history of the area with respect to ownership is provided in BENJAMINSEN et al. (2006). The research sites of this study are located in the south-eastern part of the Leliefontein communal and a neighbouring private farm (Remhoogte).

3.16.2 Observatory description

The observatories are located approx. 4 km southeast of the Paulshoek village. The two neighbouring sites are separated by an east-west stretching fence separating the communal land tenure in the north from the commercial farm in the south (see Figure 157). Both observatories are characterised by a set of typical landforms of the area with valley, slope and outcrop areas. The topography is undulated with slopes of different inclination and valley structures with a more levelled character. The sites are dominated by granitic hills, especially the northeastern part of Leliefontein and the southwestern part of Remhoogte. Heights differ from 1010 to 1122 m asl with highest differences in the Leliefontein observatory. Two riviers stretch from the northwest to the south across the observatory Paulshoek and then pass as a united rivier through Remhoogte. Compared to landscapes with a similar topography, the depth of bedrock in the slightly elevated areas is surprisingly shallow. Except for the rivier and accompanying banks, the substrates are very shallow and show a high percentage of rock fragments. This provides both, restricted soil resources and high heterogeneity on the small scale.

Upper slopes and outcrops typically have a heterogeneous surface structure characterised by boulders and bare surfaces of granitic bedrocks with intermediate patches of soils. This structure favours additional water supply by run-off/run-on processes and is thus predominantly vegetated by larger shrubs. Valleys and lower slopes have a lower heterogeneity and are characterised by smaller leaf succulent shrubs. Here, the most differentiating factor in the abiotic site conditions is the weathering status and the structure of the shallow soils, which show distinct physical soil conditions with respect to the bedrock microstructure (e.g size of boulders and fissures). Compared to the previous observatory Soebatsfontein, heuweltjies only occur occasionally and are therefore of minor importance for the small-scale vegetation structure. An important driving factor for the vegetation structure and species composition is grazing pressure, which heavily influences the vegetation pattern in Paulshoek. As a result, many sections of the easily accessible plains and slopes are dominated by *Galenia africana*, an indigenous, but unpalatable shrub that clearly indicates overgrazing. On Remhoogte, only one small patch with *G. africana* occurs on a sandy habitat close to the rivier.

Figure 156 Panorama view of the observatory #24 (Leliefontein) towards the east with typical range of habitats

Due to the importance of topography, four habitat types were distinguished as i) plain / pediment with deeper soils, ii) slopes with gravel, iii) slopes with boulders, and iv) rivier (see Figure 156).

The typical fenceline contrast has attracted several studies in the region (e.g. TODD & HOFFMAN 1999, ALLSOPP 1999). ANDERSON & HOFFMAN (2007) investigated the impact of such contrasts in vegetation in commercial and communal areas of the wider region. Another study analysed the influence of land-use intensity on insect diversity and pollination services on the two observatories directly (MAYER 2005).

3.16.3 Soils

3.16.3.1 Main soil units

25 soil profiles on each observatory were examined according to the standardised ranking procedure. On the commercial farm Remhoogte, a transect through the exceptional patch with *Galenia africana* was documented additionally with five profiles. The soil units of the observatories #24 and #25 and their distribution are provided in Figure 157.

According to the WRB (1998), six reference groups were found (Figure 158). Due to the rocky character of the area, the majority of the profiles is classified as Leptosols, followed by Cambisols on the lower slopes and Fluvisols along the rivier structures. Soils with fluvic properties in certain locations are enriched with soluble salts allowing the qualifier 'salic' and, in one case, the classification as a Solonchak. The Cambisols, characterised by profiles > 25 cm, loamier textures and signs of clay translocation from top to subsoil are assumed to be the oldest soil units on the observatories. Younger and coarser textured profiles occur sparsely and are classified as Arenosols. A unique soil has developed in the only heuweltjie structure found on the observatory Remhoogte. Here, biogenic accumulation of calcium carbonate results in a classification as Hypocalcic Calcisol. The differentiation of the soil units into Leptosols, Cambisols and Regosols is mainly based on depth of bedrock as well as the content of coarse fragments. In addition to these soil physical properties, the qualifiers 'dystric' and 'eutric' already stress the wide range of soil chemical properties in the Leptosols.

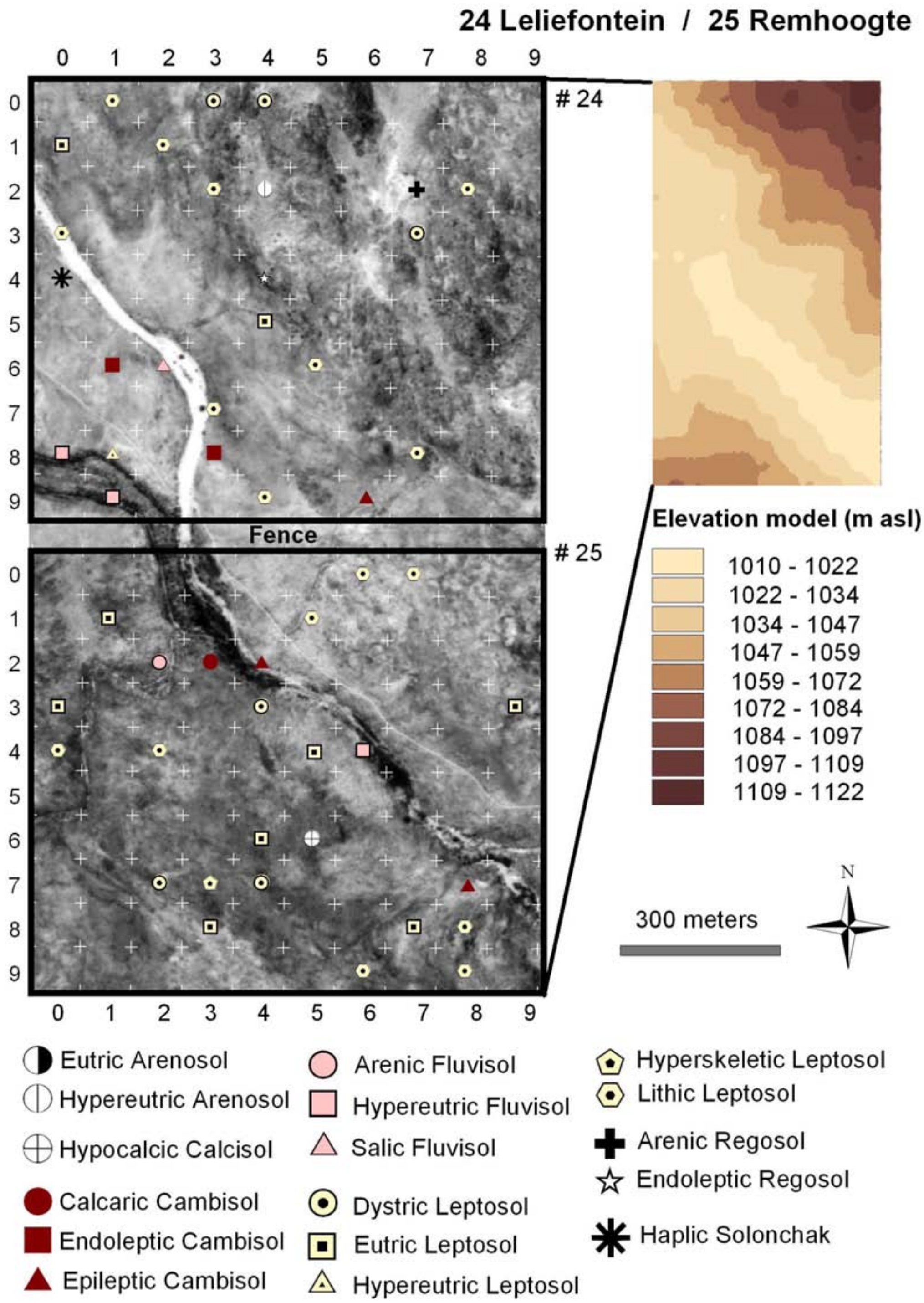


Figure 157 Distribution of soil units on the observatories #24 and #25 (Ranking 1-25, 1st - qualifier level)

Please note that the Eutric Arenosol also found on plot 23 Remhoogte is without signature.

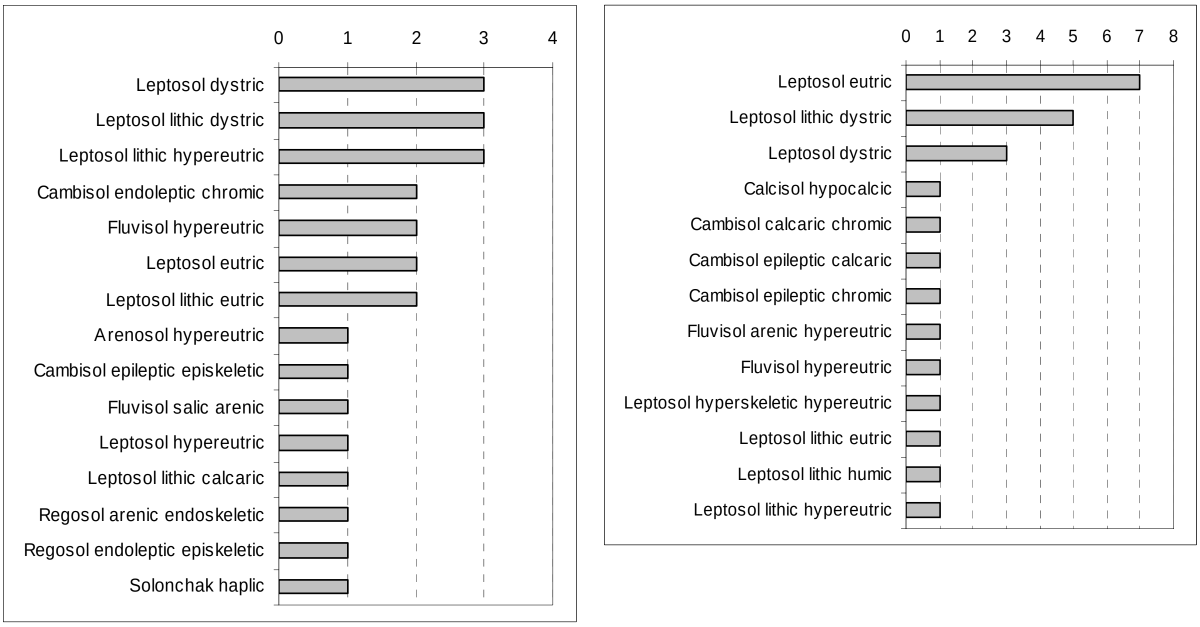


Figure 158 Frequency distribution of WRB soil units in observatory #24 Leliefontein (left) and #25 Remhoogte (right)

3.16.3.2 Remarks on classification

The classification of the soil units is provided in the WRB (1998) nomenclature. The most important features and the differences of these soils (shallow bedrock, coarse fragment content, cambic horizon, base status and partly fluvial genesis) could be described sufficiently with the applied qualifiers and reference groups. Although the striking impact of heuweltjies on soil properties (see #22 Soebatsfontein) is not very evident in this region, the classification reflects a wide variety of abiotic site conditions.

The application of the new version of the WRB (2006) reveals only minor changes. Only the newly introduced qualifier 'clayic' allows a more precise naming of the heavier textured Cambisols.

3.16.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **1148**	Ha: **94** Obs. **25**	Classification (WRB 1998) **Dystri-Lithic Leptosol** (WRB 2006) **Lithic Leptosol (Dystric)**

cm	Horizon	Description
		Accumulation of coarse fragments, 90 % cover
5	Ah	Loamy sand (Su2), 80% fragments, single grain structure, grey-brown, Munsell 10YR5/4 dry and 10YR3/3 moist, 11-20 roots/dm^2, low excavation difficulty
6	R	Bedrock

Figure 159 Description of profile 1148

The Dystri-Lithic Leptosol is the typical soil unit found on slopes, rocky areas and even on only slightly inclinated plains. The shallow bedrock and a high fragment content cause a small-scale heterogeneity of available soil resources, but offer limited general water storage capacity in the soil. In this profile, the gneissic-granitic bedrock of 6 cm in depth exhibits few signs of weathering; it is only penetrable by roots along few fissures. In Figure 159, the aspect of such a typical site is shown. The rocky character is well visible by the fragment-rich surface.

The fine earth of the non-calcareous soil is composed of loamy sand (Sl2) with a dominance of medium sand. The pH-value is very strongly acid and $EC_{2.5}$ is low with 130 µS cm^{-1}. Organic carbon is relatively high with 0.9 %.

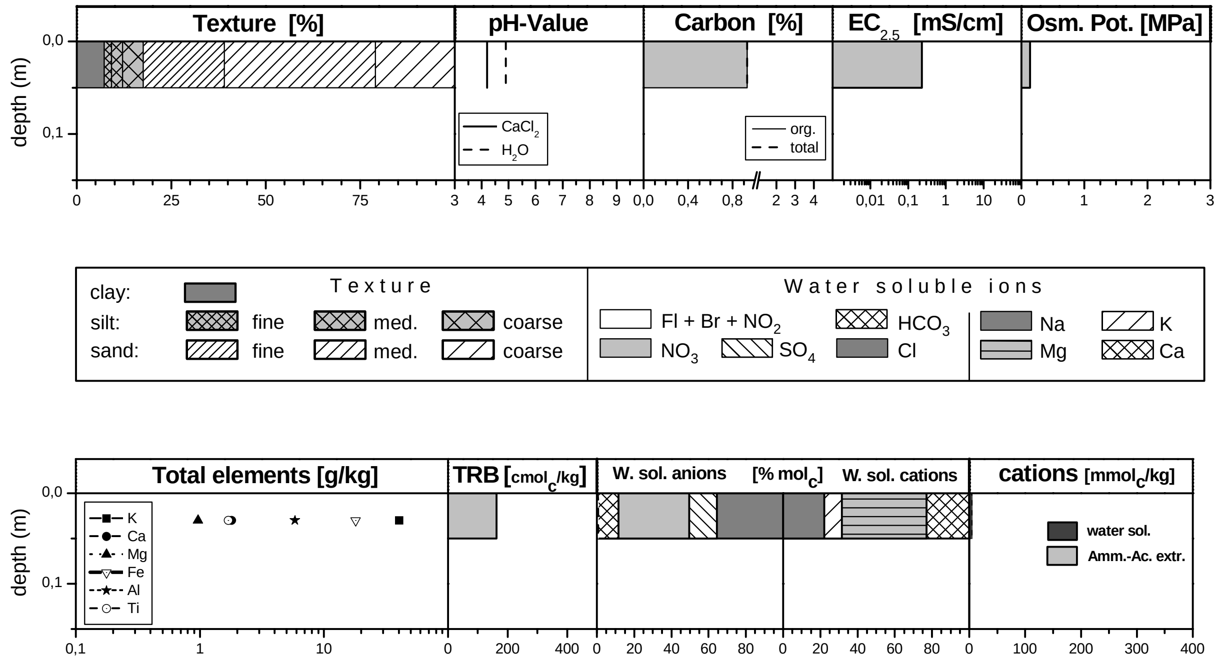


Figure 160 Properties of profile 1148

Reference profile # 2

Profile: **1145**	Ha: **78**	Classification (WRB 1998)	**Chromi-EpilepticCambisol**
	Obs. **25**	(WRB 2006)	**Epileptic Cambisol (Eutric, Clayic, Chromic)**

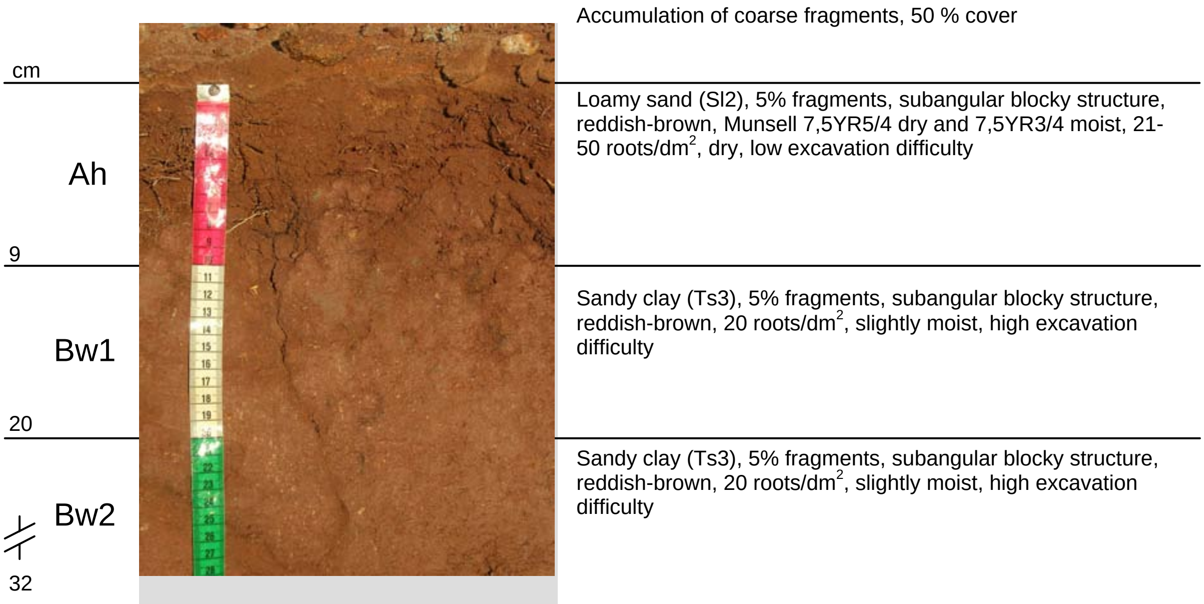


Figure 161 Description of profile 1145

The Chromi-Epileptic Cambisol of Figure 161 is a typical example for the older and deeper developed soils of the lower slopes. The field observations indicate that these Cambisols are predominantly found on westerly-exposed sites, which might additionally receive run-on water from higher positions. The texture of this profile is sandy clay with topsoil consisting of loamy sand. Clay content increases strongly from 9 – 30 % from the first to the second horizon, which shows clear signs of columnar macro structure. The pH-value is slightly acid in all depths and the generally low $EC_{2.5}$ shows a slight increase with depth from 30 to 90 µS cm^{-1}. Organic carbon is nearly constant with comparably low values of 0.4 %.

With regard to textural changes, the total element contents are surprisingly constant with depth except for an increase in Mg and Fe. Remarkable is the constant trend of Al, which normally follows the clay trend in such substrates. This may be an indicator of a different clay mineralogy in the first and second horizon.

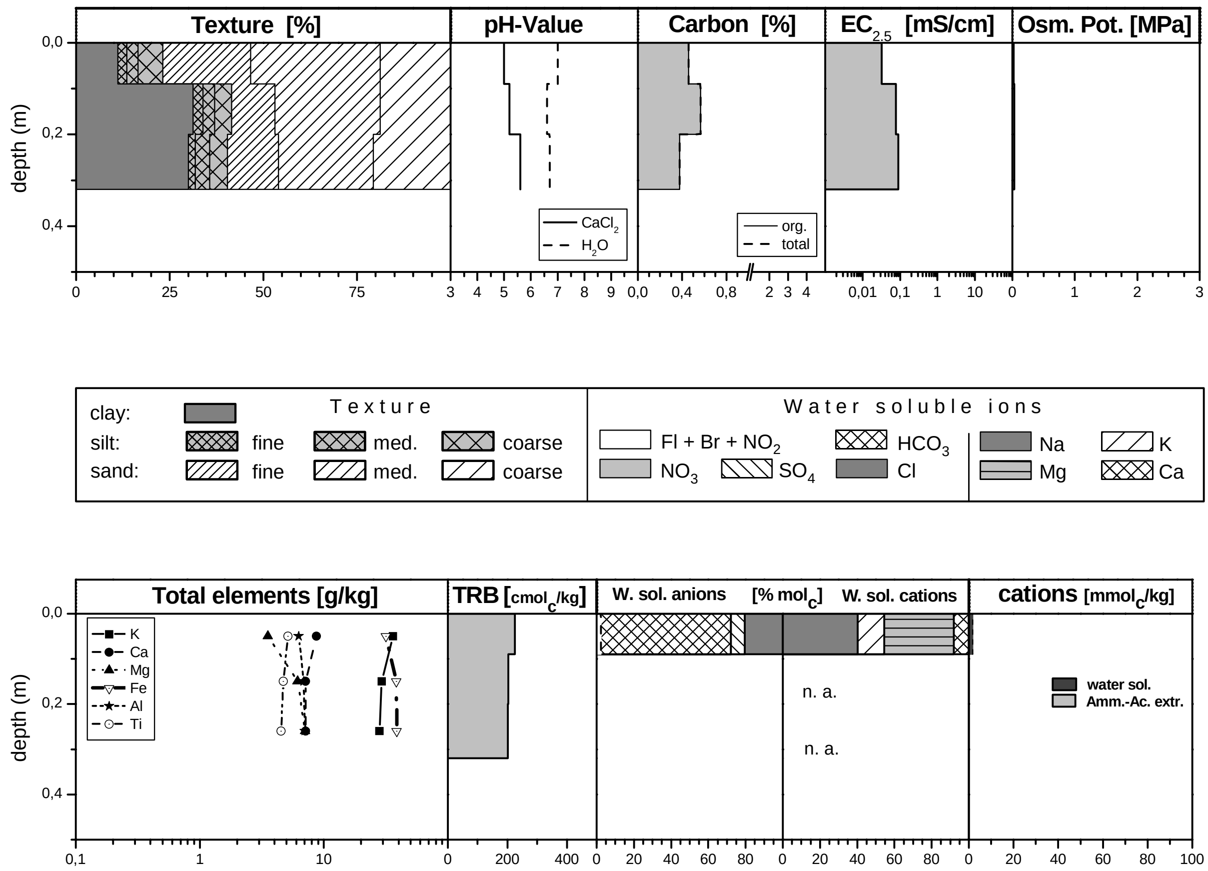


Figure 162 Properties of profile 1145

Reference profile # 3

Profile: **1169**	Ha: **24** Obs. **24**	Classification (WRB 1998) **Hypereutric Arenosol** (WRB 2006) **Haplic Arenosol (Hypereutric)**

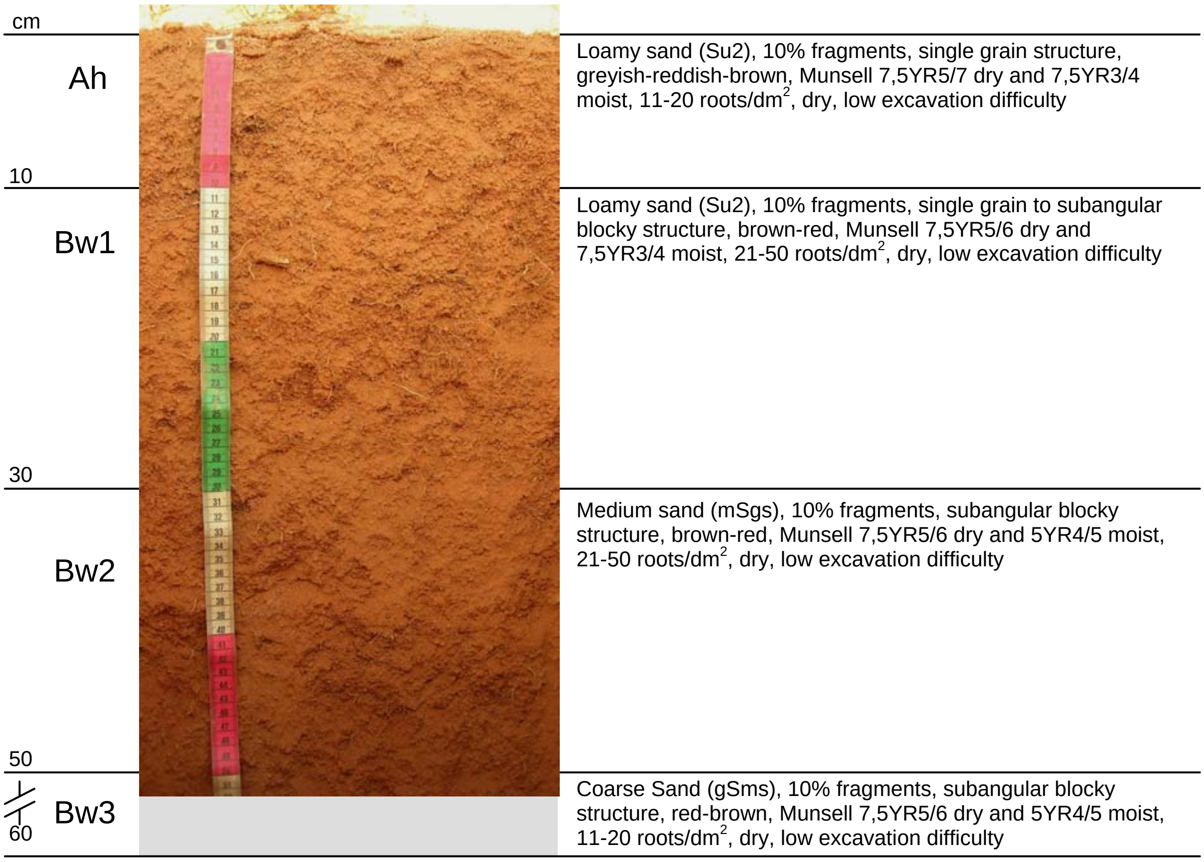


Figure 163 Description of profile 1169

The third reference profile, which has only been found once, is a Hypereutric Arenosol developed in a small basin structure filled with sandy weathering products of the granites. These basin structures occur infrequently along the slopes and are the result of small terrace structures behind ridges or large boulders. Typically, these substrates are free of coarse bedrock fragments but inhabit different amounts of small gravel. In this profile, the amount of gravel is low with only 10 %. The main texture is loamy sand consisting of more coarse than medium sand.

The pH-value is neutral and stays - like the low $EC_{2.5}$ - constant with depth. Except for organic carbon and total Mg, which increases slightly with depth, this homogenous structure is valid for all parameters.

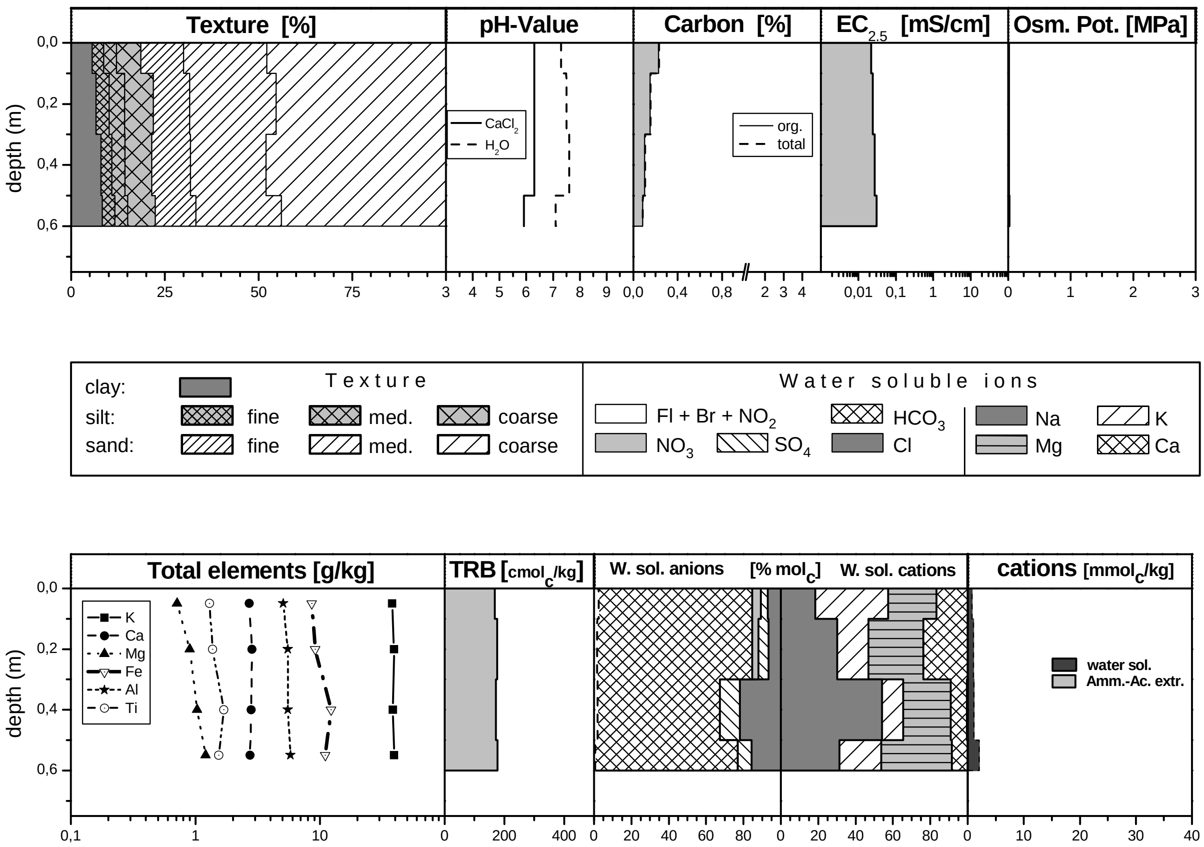


Figure 164 Properties of profile 1169

3.16.3.4 Discussion of soil properties

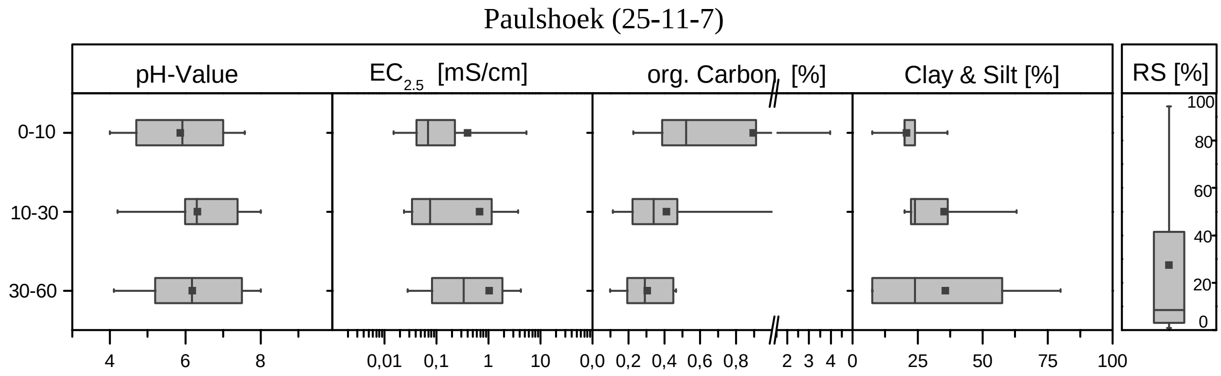
Figure 165 depicts the variability of selected soil properties in three different depth intervals for the neighbouring observatories based on data of 25 profiles each.

The pH-values show a wide range and some variations with depth, mainly characterised by an increase in the second horizon, and on Remhoogte additionally in the third horizon. The low median values of $EC_{2.5}$ increase with depth but reflect the non-salty character of the environment in the observatories. However, wide ranges show the presence of single salt enriched sites, especially on the Leliefontein observatory.

A high variability combined with a general decrease with depth is observable in organic carbon reflecting the varying amounts of humus accumulation which is due to the different site conditions. The fine particle percentage (clay & silt) shows narrower boxes with a slight increase in depth and wider ranges only in the subsoil of Leliefontein.

The median rooting space (RS) of 10 % in Leliefontein and 5 % in Remhoogte represents the overall shallow and rocky character of the area, but single deeper profiles also show a wide range of rooting available fine earth. Here, the higher RS values for Leliefontein are a result of a higher percentage of low-lying valley soils, which tend to provide higher fine earth content.

In general, the high variability of the observatories is described by both, the total range of parameters and wide boxes, which indicate an even distribution of these different site properties except for the silt & clay percentage, and by the RS, which are dominated by the overall silty sand and shallow character of the soils.



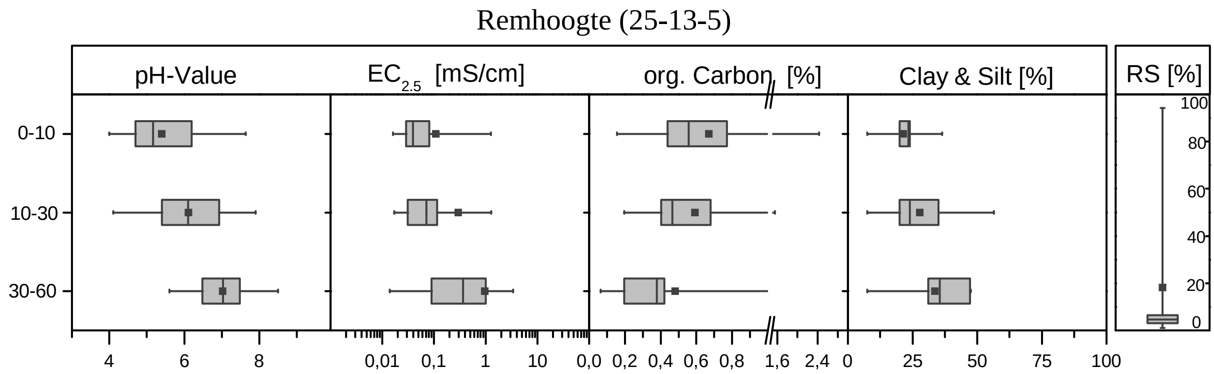


Figure 165 Variability of selected soil properties in three depth intervals for the observatories #24 and #25

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

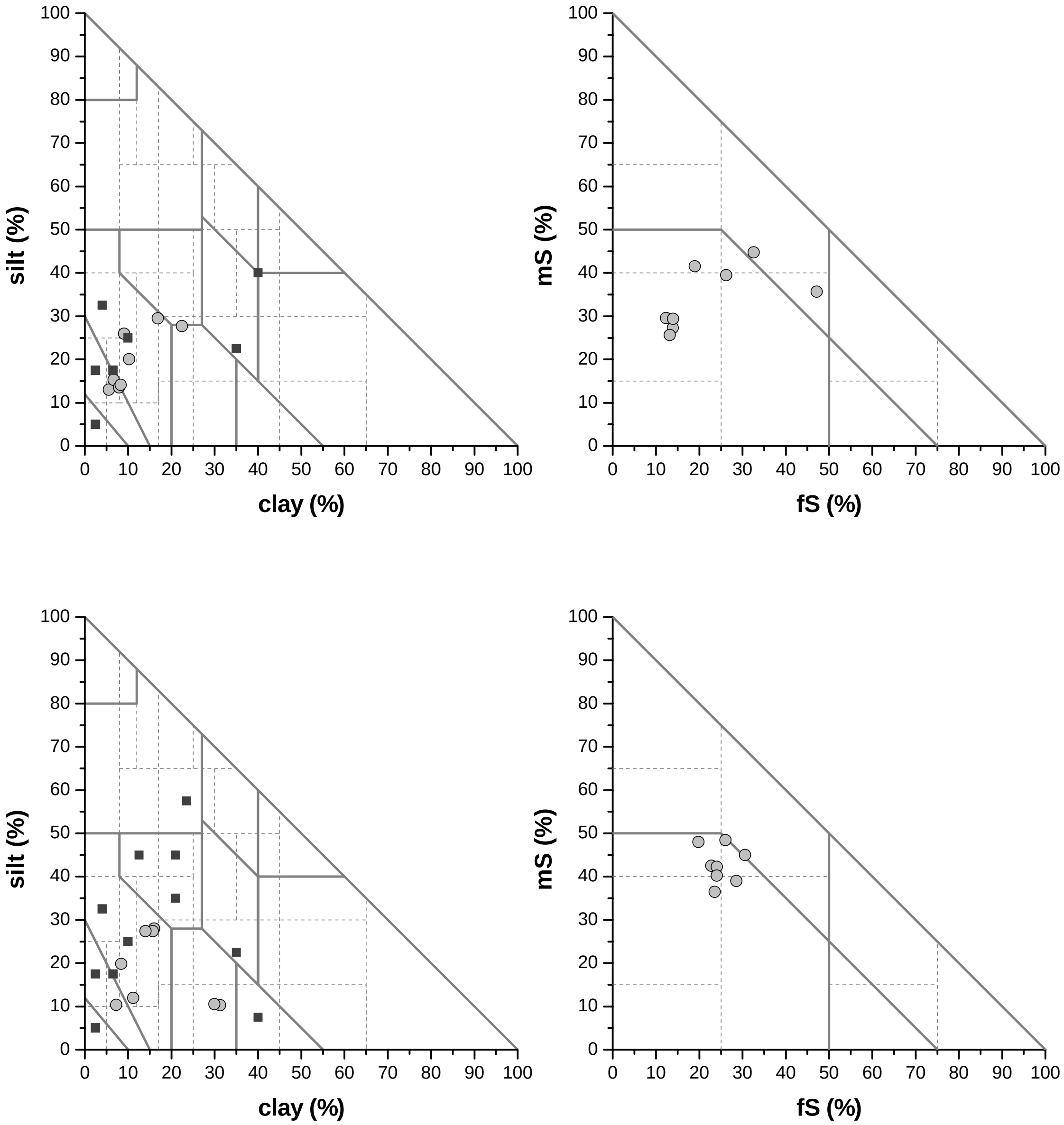


Figure 166 Results of the combined texture analyses for the observatories #24 (above) and #25

Squares = finger test (all samples) and circles = lab analyses (selected samples)

The texture (Figure 166) is mainly characterised by silty and loamy sand except for few Cambisols with a clay rich loam texture. With regard to the sand fractions, the samples are predominantly coarse sands (by FAO 2006, mSfs and mSgs by KA5) characterising the typical weathering product of gneissic granitic bedrock.

With respect to the analysed soil profiles, it can be concluded that both observatories are comparable in their abiotic environment. However, conditions are not utterly similar, as profiles on the Remhoogte site are a little less deep, while the Leliefontein site inhabits outcrops, which are 50 m higher than highest points in Remhoogte. Furthermore, the rivier habitat proportion is higher in Leliefontein.

Pattern analogies in the soil and vegetation distribution go along with topographic features on different scales. On a broader scale, the degradation aspect, underlinedby higher proportions of *Galenia africana* and lower plant coverage in general, is the most visible feature along the fenceline. Although *G. africana* is assumed to influence soil chemical properties by increasing the pH-value (ALLSOPP 1999), in this study a utilisation-based effect on the soils is not detectable with regard to the site conditions of *Galenia africana* patches. Besides the advantage *G. africana* exploits with overgrazing, it is well observable that this species is predominantly found on sites with deeper, sandier profiles. This is also true for a deeper sandy soil patch on the Remhoogte observatory where a low grazing pressure is evident while *G. africana* is very frequent. The reason why this species is so dominant in particular sandy soils is not yet clear. It may be that i) as sandy sites are more homogenous in soil structure, they comprise fewer microhabitats with respect to an irregular rooting space and the availability of rainwater. It seems that *Galenia africana* is well adapted to this homogeneity. ii) Another important factor might be the fact that sandy sites and plains are often easier accessible by animals and thus experience higher grazing pressure. However, in case of the *Galenia* patch in Remhoogte this is not true as the patch is surrounded by another species composition (‘non-overgrazed’) on comparable topography. However, the stone-free surface of the soil might nevertheless offer a preferred resting place for animals in comparison to the surrounding stony plains. iii) It may also be that the patch represents a remnant of a generally denser coverage of *G. africana* a few decades ago, possibly initiated by fallow activities. Benjaminsen et al. (2006) show similar aspects between the two observatories for a time period 30 years ago by comparing aerial photographs differing enormously from today with very distinct aspects along the fence. The authors conclude that severe over-utilisation took place over a period of several decades, which was then followed by a relatively fast recoverage on the fenced site Remhoogte with low grazing pressure. This hypothesis might explain the small island of *G. africana*.

On a smaller scale, a less visible but ecological highly important soil feature is responsible for the diversity of site conditions. In a semiarid system like this, the availability of water is crucial and overrides most of the soil chemical difference. Although the area is dominated by Leptosols and therefore seems to be homogenous regarding the physical conditions in the shallow soils, astonishing differences occur on the micro scale. Due to different weathering behaviour and micro-tectonic features such as faults and fissures, a range of Leptosols can be distinguished with respect to their bedrock facies and size of fragments. I distinguished four different kinds of water supply types. Habitat aspects of these types are shown in Figure 167. The basic principle is a differentiation from type 1 with large boulders generating high run-off and a strongly heterogeneous ‘rock-garden’ structure to the most homogenous site conditions in the Leptosols, categorised as type 4. Here, a small-scale pattern of cracks and fissures combined with a vertical orientation of most fissures generates a homogenous distribution of water and results in a less diverse pattern of plant species. Additionally, a better accessibility might result in stronger grazing impact on these sites.

Figure 167 Four typical aspects of Leptosols with different site conditions caused by weathering behaviour of the bedrock

During the field survey in September 2005, many (very recent) erosion features were mapped on both observatories. The local community reported an extraordinary thunderstorm with heavy precipitation in early April 2005. This unusual summer rain of around 80 mm (BIOTA weather data) created heavy run-off leading to sheet and gully erosion on both observatories, irrespective of the grazing intensity.

This recent thunderstorm showed how vulnerable these winter rainfall adapted ecosystems are to strong rain events.

In particular the typical soil surface with frequent bare patches and succulent vegetation with its low coverage values is only adapted to the low intensity of winter rainfall typical for this area. Erosion hardly ever takes place under these slowly dripping, but long lasting rain events, which allow an almost complete infiltration of water. In the case of heavy summer rainfall events, neither the often bare soil nor the vegetation can reduce the intensity and enhance infiltration as is the case for grasses in savannas with a more homogenous and denser structure. However, denser grass covers are untypical for the winter rainfall regime and occur rarely. Soil erosion is therefore a considerable problem with changing rainfall regimes.

Highly intense summer rainfall events are rare but not atypical for this region, which is adjacent to the ecotone of the summer rainfall driven Bushmanland in the east. With regard to global change scenarios, it can be expected that a shift to a higher percentage of summer rainfall and a decrease of winter rainfall will occur (see MACKELLAR et al. 2007, RICHARDSON et al. 2007). This will have an enormous impact on both, soil and vegetation of the region. Maintaining the soil resources that developed under the winter rainfall climate will be more difficult under a changing rainfall regime. Additionally, stronger precipitation events will decrease the amount of water available for the ecosystem because of higher run-off rates and increasing aridity.

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3.17 Observatories 26 Flaminkvlakte (Goodehop) & 27 Luiperskop (Ratelgat)

3.17.1 Regional overview

The Knersvlakte represents the southern border of the Namaqualand. Two observatories are located in this broad peneplain, which developed some 20 million years ago due to the proto-Orange River (DESMET 2007). Geologically, the Knersvlakte separates the igneous Namaqualand Metamorphic Complex in the north and the sandstone and shale sedimentary rocks of the Cape Fold Mountains in the south and represents a gap in the surrounding escarpment. The lithology is mainly characterised by shales and phyllite of the Gifberg formation (Vanrhynsdorp Group).

The region is situated on a mean height of 150 - 250 m asl in the plains with heights around 800 m in the east bordering the Bokkeveld escarpment. The topography is characterised by level plains and low relief hills comprising quite a featureless structure. Most prominent features of the landscape are island-shaped areas covered with whitish quartz gravel originating from numerous shattered quartz veins in the sedimentary rocks (see Figure 168).

The vegetation type is called Knersvlakte Quartz Vygieveld (MUCINA & RUTHERFORD 2005), a flora rich in dwarf succulents belonging to the Knersvlakte bioregion of the Succulent Karoo Biome. According to SCHMIEDEL and JÜRGENS (1999), the area can be described as the centre of diversity and endemism for the quartz flora of southern Africa. Spatial micropatterns of various vegetation units with a distinct composition of growth forms are characteristic for this landscape. These abrupt floristic changes across quartz field boundaries are associated with edaphical changes, especially in pH-value and salinity (SCHMIEDEL & JÜRGENS 1999, SCHMIEDEL 2002, see also Figure 169) as well as with microclimatic changes (SCHMIEDEL & JÜRGENS 2004). A recent study regarding the unique flora and its environmental relationship describes the role of soil microenvironment for the local adaptation of various *Argyroderma* species (ELLIS & WEIS 2006).

The Sout Rivier provides the main drainage for the Knersvlakte, running towards the west. Annual Rainfall is around 100 – 175 mm with predominantly winter rainfall (SCHMIEDEL & JÜRGENS 1999). Additional precipitation occurs through occasional coastal fog (VAN WYK & SMITH 2001).

Land-use in the area is small stock farming in fenced camp systems.

Figure 168 Overview of a typical quartz-dominated aspect of the Knersvlakte in the observatory #26 Flaminkvlakte

3.17.2 Observatory description

The observatories are located 45 km north of Vanrhynsdorp. They are directly next to each other, merely separated by a fence. The northern observatory on the Flaminkvlakte farm belongs to a commercial small stock farmer. The stocking intensity with mainly sheep is low. The southern observatory is located on the Griqua-farm Luiperskop (Ratelgat). Since 1999, the farm belongs to the Griqua Development Trust. The Griqua Community, which is partly based in Vredendal, uses the farm for cultural, educational and economic (i.e. small stock farming and ecotourism) purposes. After having been used for moderate commercial small stock farming for several decades, the farm is now subject to a low grazing intensity (www.biota-africa.org).

The entire area belongs to the quartz field dominated part of the Knervlakte. Most parts of both observatories are characterised by these quartz fields. The topography is slightly undulated to rolling with slopes, plateaus and valley structures of small riviers draining towards the Sout River. In general, the northern observatory shows a more heterogeneous relief than the adjacent site. This is due to branching of small rivier structures dissecting the plains into many fragments, while the observatory Luiperskop is characterised by only one large catchment and rivier draining to the southeast. Heights in both areas range from 212 m asl to 253 m asl with the highest points on Flaminkvlakte. Underlying and often exposed lithology comprises mainly phyllites and partly schists, which are more resistant against weathering. Quartz veins streak both observatories, the source for the typical quartz gravel on the soil surface. Main substrates are silt-dominated loams of various depth with high content of quartz fragments.

The observatories are dominated by leaf succulent dwarf shrubs and both are very species rich. The genera of Aizoaceae and Asteraceae are the most diverse groups in these sites (www.biota-africa.org). Typical for the observatories is a small-scale pattern with high changes of species composition within a few metres (Figure 169). The drainage lines are characterised by denser stands of *Galenia africana*.

Figure 169 Aspect of the typical small scale change of soil and vegetation patterns on the Flaminkvlakte observatory: from left to right (approx. 4 m): *Drosanthemum diversifolium and Cephalophyllum spissum* community with low to medium salt stress, centre *Argyroderma deleatii* community with medium to high salt stress, right extremely salty topsoil without plants and a puffy, salt-dynamic structure

Six habitat types were distinguished based on the topography and the occurrence of quartzes on the soil as i) quartz dominated slopes and plains, ii) small scale quartz / non quartz mosaic, iii) quartz hills with rivier structure, iv) slopes and plains with non-quartz surface, v) quartz fields with shrubby vegetation, and vi) quartz fields in salt pan depressions.

3.17.3 Soils

3.17.3.1 Main soil units

25 soil profiles were examined on each observatory by means of the standardised ranking procedure. The frequency of resulting soil units and their distribution are provided in Figure 170 and Figure 171. According to the WRB (1998), the reference groups Cambisol, Leptosol, Fluvisol, and Solonchak are found. The reference groups are evenly distributed across both observatories except for the Fluvisols, which do not occur on Luiperskop. On the two-qualifier level, the Hypersali-Yermic Solonchak is the most frequent soil unit and characterises the saline quartz fields. Cambisols are found on less saline substrates and are characterised by an intensive red, loamy texture, often densely packed with residual quartz debris. The endo- and epileptic qualifier additionally characterises the depth of this profiles with respect to the underlying bedrock. The shallowest soil unit, Leptosols, are found on shallow phyllite and schist bedrock or larger quartz outcrops. The Leptosols are further divided by means of the dystric and eutric qualifier, reflecting the wide range of base saturation.

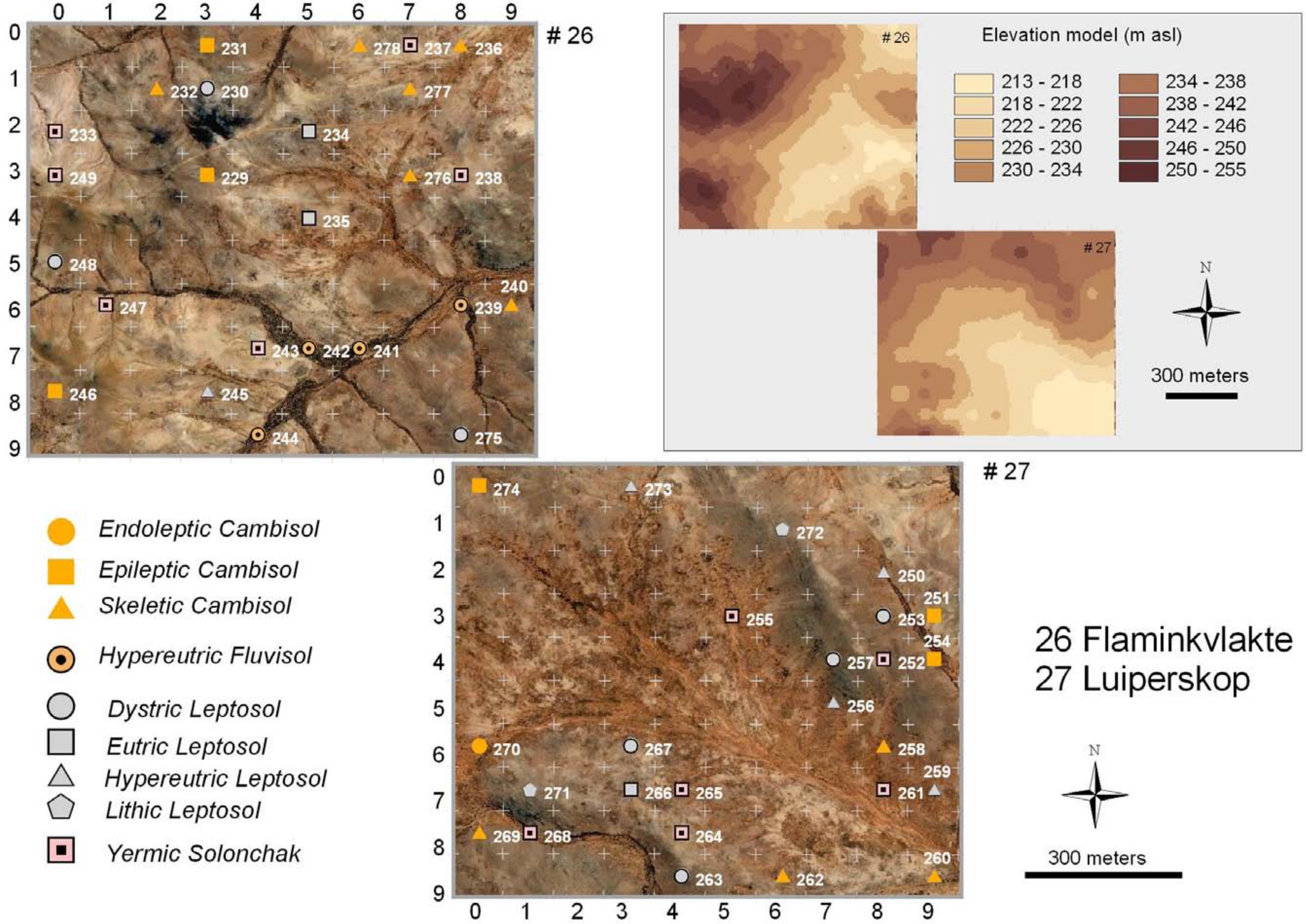


Figure 170 Distribution of WRB soil units (1998, 1st qualifier-level) and DEM of the observatories #26 and #27

The Hypereutric Fluvisols are exclusively found on the Flaminkvlakte observatory. They are characterised by a high pH-value and a dense bush cover of *Galenia africana*, well visible on the aerial photography because of its dark appearance. The Fluvisol is the only soil unit that can be clearly assigned to a topographical position, while the occurrence of the other soil units is only driven by small-scale changes of varying bedrock depth and enrichment of soluble salts.

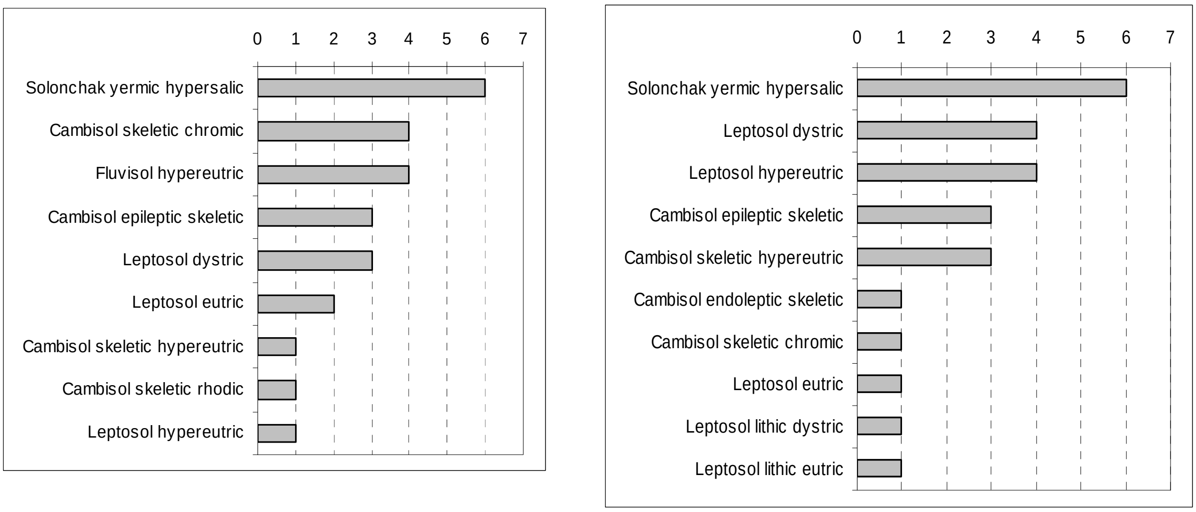


Figure 171 Frequency distribution of WRB (1998) soil units in observatory #26 Flaminkvlakte (left) and #27 Luiperskop (right) (2^{nd} qualifier level)

3.17.3.2 Remarks on classification

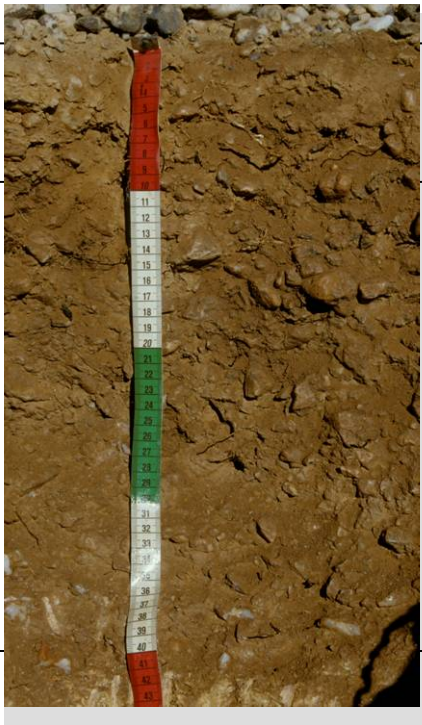
The classification of the soil units is provided in the WRB (1998) nomenclature. Some important features and differences of these soils (limitations by bedrock, fragments, texture, fluvial genesis and base status) could be described sufficiently with the applied qualifiers and reference groups. However, with respect to soil salinity,a basic problem in the WRB is evident. Many profiles are strongly affected by salt which cannot not be expressed by the ranked qualifiers in the above described reference groups, however. Due to the requirements for the assignment of a salic horizon for a Solonchak which is based on a certain product of EC_e and horizon depth the salinity of the soils could not be expressed as they are too shallow. At the same time, the soils are prominently driven ecologically by the high salt contents. I therefore decided to classify those soils with ECe > 30 mS cm^{-1} in the 1^{st} horizon as Solonchak to express the saline character, which is not possible in the reference group of Leptosols where most of these profiles would remain. Additionally, in the case of saprolitic bedrock, which often occurs in a soft schist derived facies in depths between 10 and 50 cm, a major problem is the failure of different diagnostic criteria: i) the definition for continuous hardrock does not allow Leptosols, and ii) the autochthon bedrock structure excludes the possibility of defining a Cambisol, although the saprolite behaves like fine earth of a cambic horizon. Nevertheless, in these cases I decided to classify a Cambisol instead of defining the new unit of Regosols.

Major changes occur when the new version of the WRB (2006) is applied. The most important change is the reduction of the product requirements in the salt contents, which now ‘officially’ allows defining salic horizons in shallower soils. Moreover, the salic qualifier is also introduced to the Leptosols, which enhances the opportunity of separating saline and non-saline shallow soils. Further enhancements are the introduction of the qualifiers ‘siltic’ and ‘clayic’ for a more detailed description within the Fluvisols, Solonchaks and Cambisols. The latter now also provide the opportunity of using ‘alkalic’ for the characterisation of a high pH-value.

3.17.3.3 Description of selected reference profiles

Reference profile # 1

Profile: **229**	Ha: **33** Obs. **26**	Classification (WRB 1998) (WRB 2006)	**Skeleti - Epileptic Cambisol (Chromic)** **Epileptic Cambisol (Skeletic, Siltic, Chromic)**



Depth (cm)	Horizon	Description
		Accumulation of quartz pebbles, 90 % cover
0–10	Ah	65 % coarse fragments, silt loam (Ut3), subangular blocky structure, reddish-brown, Munsell 7,5YR6/6 dry and 5YR4/6 moist, 11-20 roots/dm^2, moderate excavation difficulty
10–40	Bw1	65 % coarse fragments, silty clay loam (Tu3), red-brown, Munsell 7,5YR5/6 dry and 5YR3/4 moist, 6-10 roots/dm^2, moderate excavation difficulty
40–45	Bw2	90% coarse fragments, red-brown, Munsell 7,5YR6/6 dry and 5YR4/6 moist, 6-10 roots/dm^2, high excavation difficulty

Figure 172 Description of profile 229

The profile shown in Figure 172 is situated on the Flaminkvlakte observatory on a southeasterly exposed slope with approx. 15 % inclination. This Skeleti-Epileptic Cambisol is a typical example for deeper soils with a high content of quartz fragments and a strong red-brown colour of the clay rich fine earth. The combination of this texture and the high content of fragments result in a very dense and massive soil structure.

The main texture of the profile is silty clay loam (Tu3) while a less clayey silt loam characterises the topsoil. As typical for quartz fields, the soil surface is covered with quartz gravel of mostly 2 – 6 cm diameter. The slightly saline soil has $EC_{2.5}$ values of around 1 mS cm^{-1}, which are constant with depth, while the strongly acid pH-value increases slightly towards the subsoil. Organic carbon reaches 0.8 % in the topsoil and decreases with depth. Total element contents show different trends: whereas K, Fe, Mg, and Al increase in the subsoil, Ca and Ti decrease. TRB of the fine earth shows a moderate value while water soluble and AM-extractable bases are relatively low.

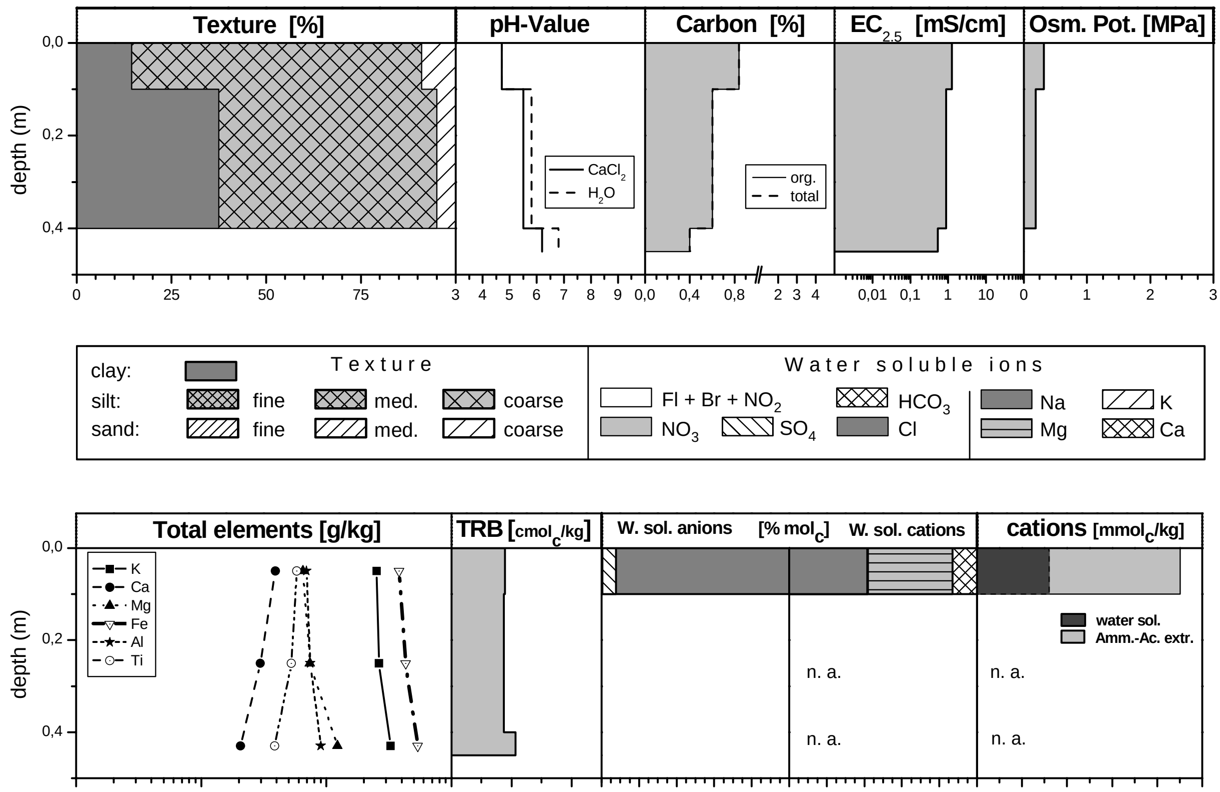


Figure 173 Properties of profile 229

Reference profile # 2

Profile: **233**	Ha: **20** Obs. **26**	Classification (WRB 1998) (WRB 2006)	**Hypersali - Yermic Solonchak (Chloridic)** **Hypersalic Solonchak (Chloridic, Yermic)**

cm	Horizon	Description
		Accumulation of quartz gravel, 100 % cover,
2	Ahz	Silt loam (Lu) with coarse sand (gSfs), loose subangular blocky structure, brownish-red, Munsell 2,5YR5/6 dry and 10R3/6 moist, 6-10 roots/dm², low excavation difficulty
7	Bwz1	Silt loam (Ut4) with coarse sand (gSfs), loose subangular blocky structure, yellowish-red, Munsell 2,5YR5/6 dry and 10R4/6 moist, 6-10 roots/dm², low excavation difficulty
12	Bwz2	Silt loam (Us) with medium sand (mSfs), loose subangular blocky structure, greyish-violet, Munsell 2,5YR6/4 dry and 10R5/4 moist, 6-10 roots/dm², moderate excavation difficulty
25	Bwz3	Silt loam (Us) with transition to original weak bedrock structure, greyish-violet, Munsell 2,5YR6/3 dry and 10R5/3 moist, moderate excavation difficulty
35	R	100% fragments = bedrock, high excavation difficulty

Figure 174 Description of profile 233

The Hypersali-Yermic Solonchak of Figure 174 is a typical example for the shallow and extremely saline soils on weathered phyllite within the quartz fields. The profile is situated on the Flaminkvlakte observatory on a northwesterly exposed slope with approx. 10 % inclination. Below the dense cover of quartz gravel follows a horizon with a loose structure of a strongly silty texture that is free of coarse fragments. This texture continues towards the subsoil while the content of weak fragments from the underlying phyllite increases. In contrast to the previous profile, the clay content is much lower, and except for the soil surface, no quartz fragments occur in the profile.

The extremely saline soil shows $EC_{2.5}$ values of around 10 mS cm^{-1} that are slightly decreasing with depth. Similarly, the pH-value changes from slightly to strongly acid with depth. Organic carbon is low representing reduced biological activity, which is underlined by the lack of plants due to the extreme osmotic potentials of > 3 Mpa. The total element contents show a strong decrease in Ca while other elements increase slightly. Water soluble and AM-extractable ions are extremely high and dominated by Na and Cl. The strong decrease in Ca is probably induced by aeolian input of material with higher Ca content in the first horizon. However, due to the absence of calcium carbonate, the input of material with a distinct geochemistry should go along with changes in other elements as well. This is not the case and the origin of the Ca remains an open question.

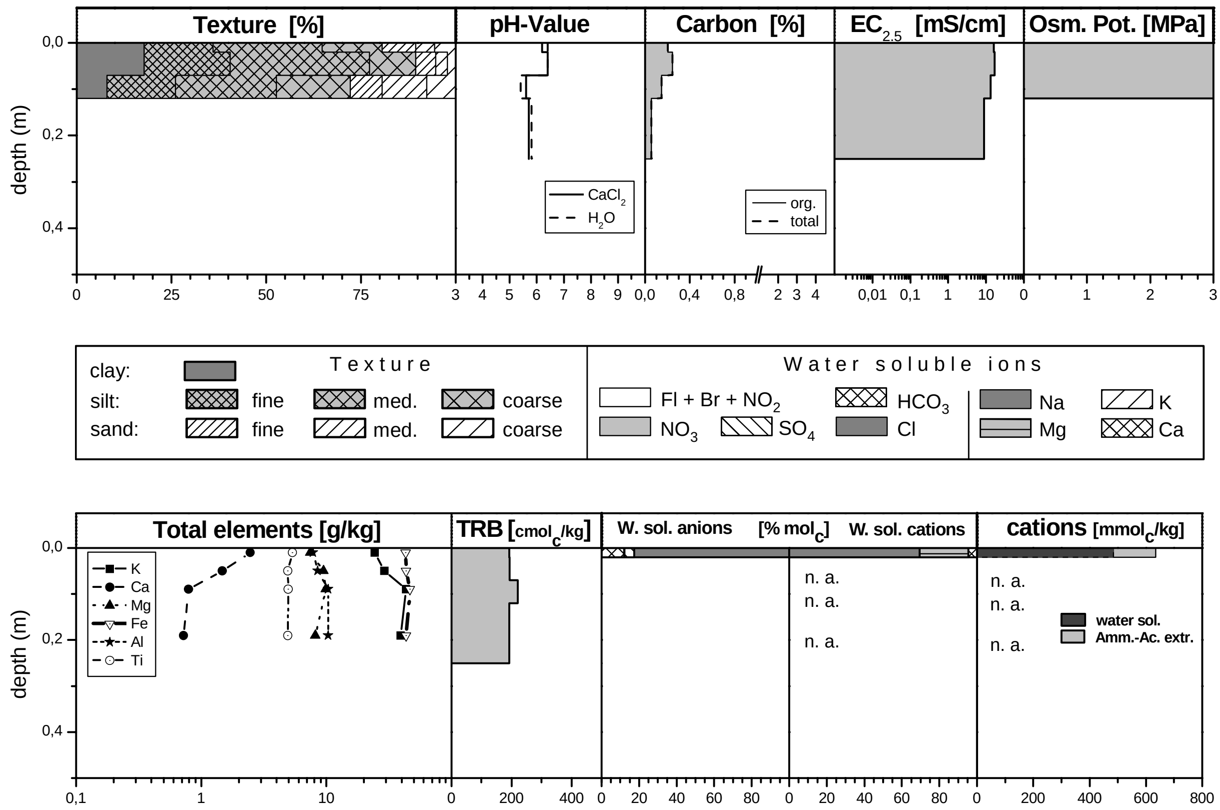


Figure 175 Properties of profile 233

Reference profile # 3

Profile: **239**	Ha: **20** Obs. **26**	Classification (WRB 1998) (WRB 2006)	**Hypereutri Fluvisol** **Haplic Fluvisol (Hypereutric, Episiltic)**

cm	Horizon	Description
2	A	Silt loam (Ut2), 5% fragments, subangular blocky to platy structure, yellowish-brown, Munsell 7,5YR5/6 dry and 7,5YR4/6 moist, light excavation difficulty
10	B1	Silt loam (Uls) with coarse sand (gSfs), 15% fragments, subangular blocky structure, yellowish-brown, Munsell 7,5YR5/6 dry and 7,5YR4/6 moist, 11-20 roots/dm^2, low excavation difficulty
20	B2	Silt loam (Ut3), 5% fragments, subangular blocky structure, yellowish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 11-20 roots/dm^2, moderate excavation difficulty
40	B3	Loam (Sl4) with coarse sand (gSfs) 40 % fragments, subangularblocky structure, yellowish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 3-5 roots/dm^2
60	B4	Loam (Ls2) with fine sand (fSms), 5% fragments, yellowish-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist, 6-10 roots/dm^2
80	B5	yellowish-brown, Munsell 7,5YR5/6 dry and 5YR3/4 moist, 6-10 roots/dm^2
90	B6	Loam (Lts) with coarse sand (gSfs), red-brown, Munsell 7,5YR5/6 dry and 5YR4/6 moist

Figure 176 Description of profile 233

The occurrence of Hypereutric Fluvisols is restricted to the riviers dissecting both observatories. These soils are typically densely vegetated with *Galenia africana*. The untypical depth of the solumn shows characteristics of fluvial deposition. The low flow intensity of the riviers is reflected in the silt-rich texture of the soil material (similar to the bedrock derived soils on the slopes and plains). The decreasing trend of organic carbon may be a result of an in situ accumulation of humus and is therefore an indication of a relatively high profile age.

The non-saline character is expressed by very low EC values of 50 - 90 µS cm^{-1}. The pH-value is moderately alkaline and constant with depth except for the strongly alkaline upper thin horizon. The fact that *Galenia africana* occurs very frequently and is concurrently suspected to increase pH-values (see ALLSOPP 1999) has to be considered when interpreting the high pH-values of the profile. The TRB varies only slightly with depth. As EC indicates, the amount of water-soluble salts is very low in contrast to fairly high AM-extractable ions.

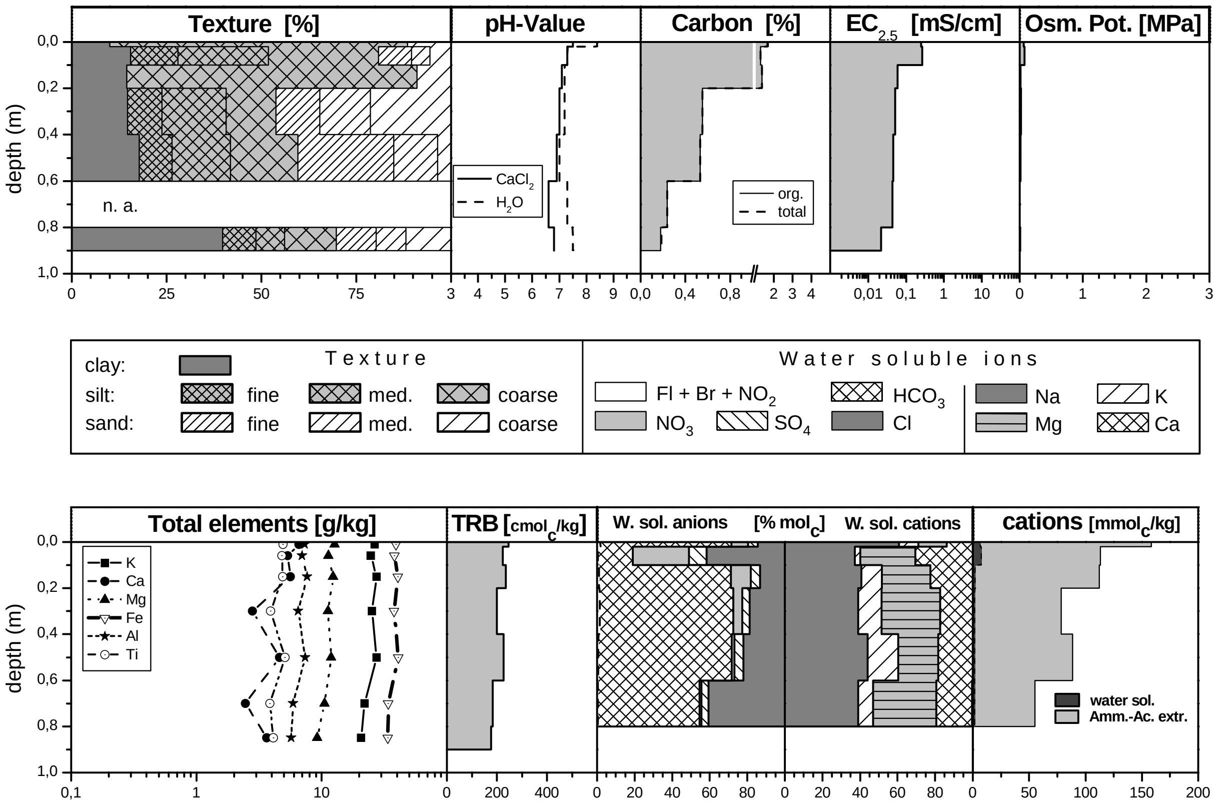


Figure 177 Properties of profile 431

3.17.3.4 Discussion of soil properties

Figure 178 depicts the variability of selected soil properties in three different depth intervals based on data of 25 profiles on each observatory. The observatories in the Knersvlakte are amongst the highest variable along the transect, especially with regard to pH-value and degree of salinity.

The pH-values show wide ranges from very strongly acid to strongly alkaline. The wide boxes indicate an even distribution of these different values. The same is true for the EC with a median of 1 m cm^{-1} indicating salt-enriched conditions, while also a high proportion of non-salt affected as well as extremely saline soils occur. The degree of salinity also affects the content of organic carbon, which shows wide ranges and a strong decrease with depth. Saline sites are regularly less enriched in OC.

The fine particle percentage (clay & silt) shows the lowest variability within the selected parameters and is characterised by the silty weathering products of the phyllite. A general trend in lower contents and wider ranges is evident for Luiperskop, which is a result of the sandier facies of the phyllites and schists on that observatory. The median rooting space (RS) indicates the shallow and fragment-rich character of the sites except for few rivier profiles with a high RS on Flaminkvlakte. Despite this difference, the soil properties and their variability are comparable for both observatories.

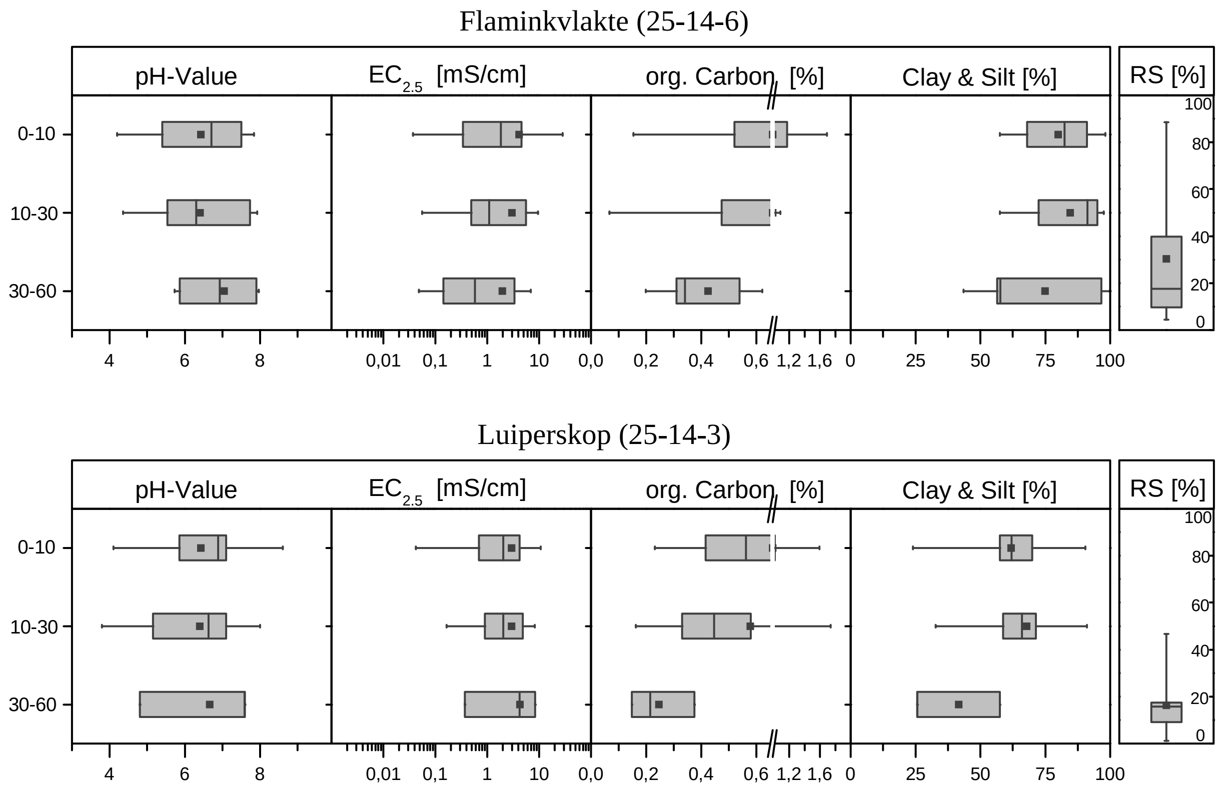


Figure 178 Variability of selected soil properties in three depth intervals for the observatories #26 (Flaminkvlakte) and #27 (Luiperskop)

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

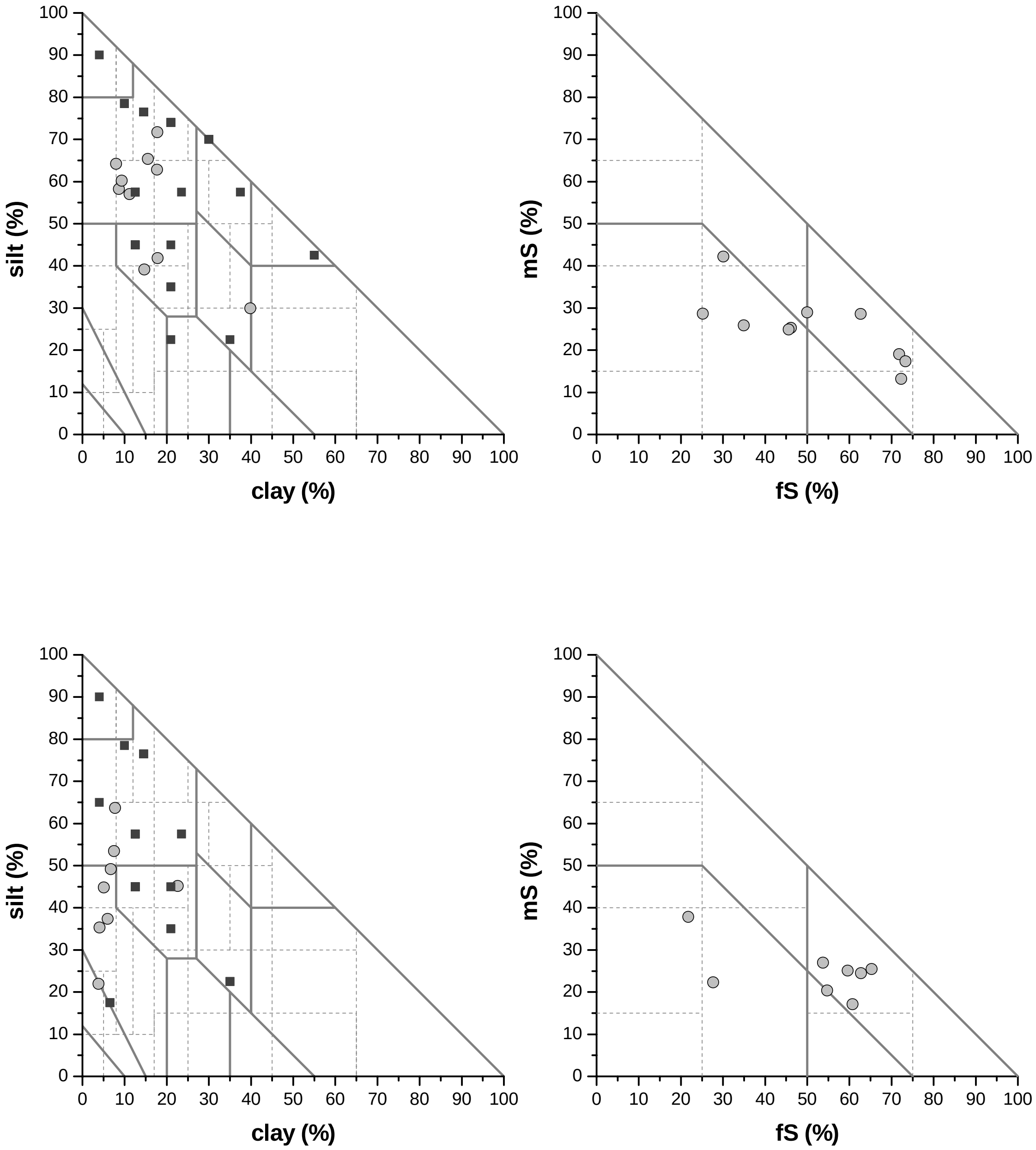


Figure 179 Results of the texture analyses for the observatories #26 (upper graphs) and #27

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 179 shows the results of the texture analyses for all samples of the observatories 26 and 27. The spectra of occurring textures are large, covering mainly silt, silt loam and sandy silt. When comparing both texture graphs, the sandier and less clayey character of the observatory Luiperskop becomes evident. With regard to the sand fractions, the samples predominantly consist of coarse and fine sands. The parent material (schist, phyllite) provides typical fine sand as weathering product; however, microfragments of phyllites occur as coarse sand in the analyses and influence the results.

Pattern analogies in the soil and vegetation distribution are clearly visible and most evident on the small scale. They are associated to changes in quartz cover and soil depth. Only the riviers with their dominant bush vegetation show vegetation that can be assigned to broader scales also. The plains, slopes and outcrops are patchy with regard to the occurrence of different soil units and thus vegetation and there is no possibility to assign these to any topographical features. In addition, the quartz cover as such cannot be used as an indicator for specific soil properties, as complete quartz coverings are found on various distinct soil and vegetation units (see reference profiles 1 and 2). The impression that there is a higher quartz cover on certain habitats is mainly due to the bare aspect of saline quartz fields, while less saline quartz-covered soils are denser vegetated and appear less white. The special relationship between soil conditions and the occurrence of certain species or growth forms and soil properties cannot be discussed in detail here and has been part of the studies in the wider area of the Knersvlakte by SCHMIEDEL & JÜRGENS (1999) and ELLIS & WEIS (2006).

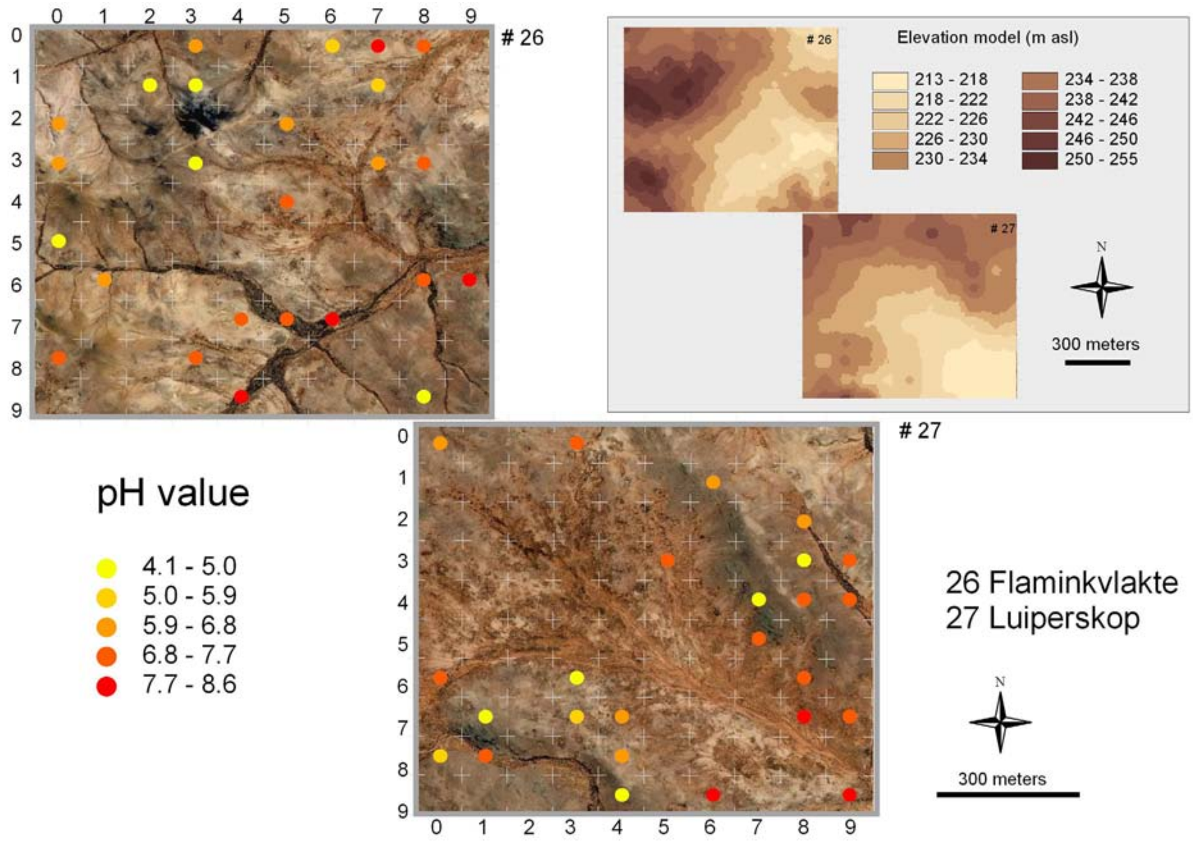


Figure 180 pH-values of topsoil (0-10 cm) on the observatories #26 & #27

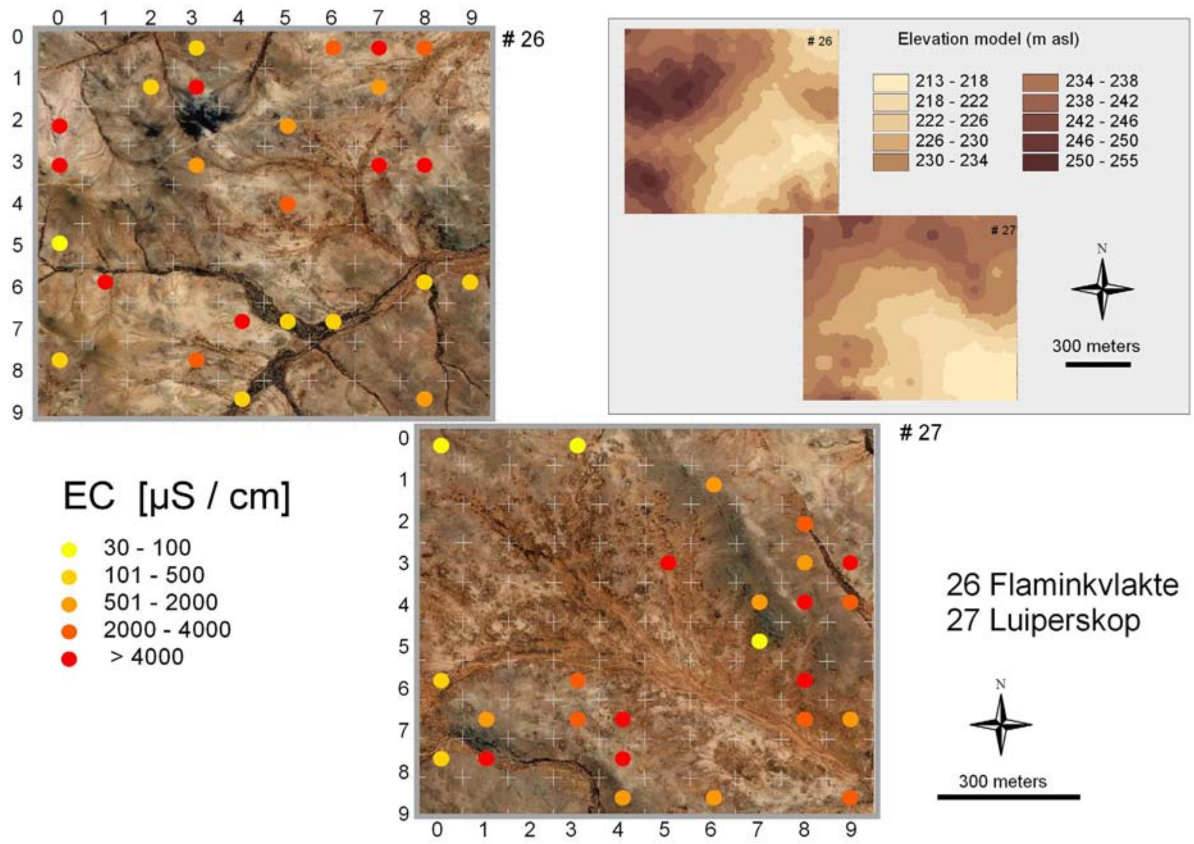


Figure 181 $EC_{2.5}$ values of topsoil (0-10 cm) on the observatories #26 & #27

Figure 180 and Figure 181 visualise the pattern of two main ecologically significant soil properties, i.e. the pH-values and salinity by $EC_{2.5}$ in the topsoil samples. Except for the riviers, the spatial pattern of these parameters is not related to topography but is basically driven by small scale change as shown in Figure 169. A basic trend is only evident for the highest alkaline pH-values, which are restricted to riviers and drainage lines. These habitats are typically not affected by salt. A relationship between EC and pH-values is not evident for the other habitats in this study. SCHMIEDEL & JÜRGENS (1999) described two main habitats (saline alkalic and non-saline acidic) with a positive correlation between salinity and pH-value.

3.18 Observatory 32 Elandsberg

3.18.1 Regional overview

The observatory #32 (Elandsberg) is located in the Elandsberg Private Nature Reserve on the Bartholomeus Klip farm at the foot of the Elandskloof Mountains in the Western Cape. Here, Fynbos vegetation of the Cape Floristic Region (LINDER 2005, BORN et al. 2007) prevails. The reserve was initially proclaimed in 1973 to protect the environment of the rare geometric tortoise (*Psammobates geometricus*).

The reserve of 3,600 ha in size is of extreme conservation value, as it also protects the most significant and single intact section of the critically endangered Swartland Shale Renosterveld and Swartland Alluvium Fynbos vegetation (MUCINA & RUTHERFORD 2005). Here, this vegetation type is associated with fertile shale soils and a rainfall regime of approx. 450 mm winter rain (adapted from CARR et al. 2006). As especially the Renosterveld is suitable for crop production, the majority of the plains have been transformed to agricultural fields and only small portions of natural vegetation remained as isolated fragments.

Geologically, the region with the reserve belongs to the Boland subgroup (Porterville formation) comprising sand and unconsolidated materials with underlying shale. This shale represents the parent material of the relatively fertile soils of the Swartland area, which is characterised by a high agricultural activity, predominantly crop farming. The finely grained soils often directly overly a saprolitic shale bedrock, which limits a deeper infiltration of soil water. This is why periods of water logging occur frequently during the rainy winter months with reduced evaporation. Anthropogenic surface drainage systems by means of small ditches and slightly elevated zones in between give the impression of marshland soils (MARQUARDT 1998). In 2005, a high run-off rate in these systems as well as strong water logging in the reserve was observed during fieldwork. The weather data from the BIOTA station recorded a total precipitation amount of 850 mm for that year. In areas towards the west where water logging is less severe, remnants of heuweltjies are clearly visible with a different topography, soil colour and different growth of the grains.

The reserve is buffered by a zone of unploughed fields in the west and bordered by the Elandskloof mountain chain in the east. The only impact on the Renosterveld is slight grazing by game of the reserve.

3.18.2 Observatory description

The observatory itself is located approx. 1 km south of the Voelvlei Dam and 1.5 km east of the Elandskloof mountain chain in the northern section of the reserve. The unploughed former farmland in the west now serves as an important buffer for the threatened pristine Renosterveld habitat and as a monitoring site for succession studies.

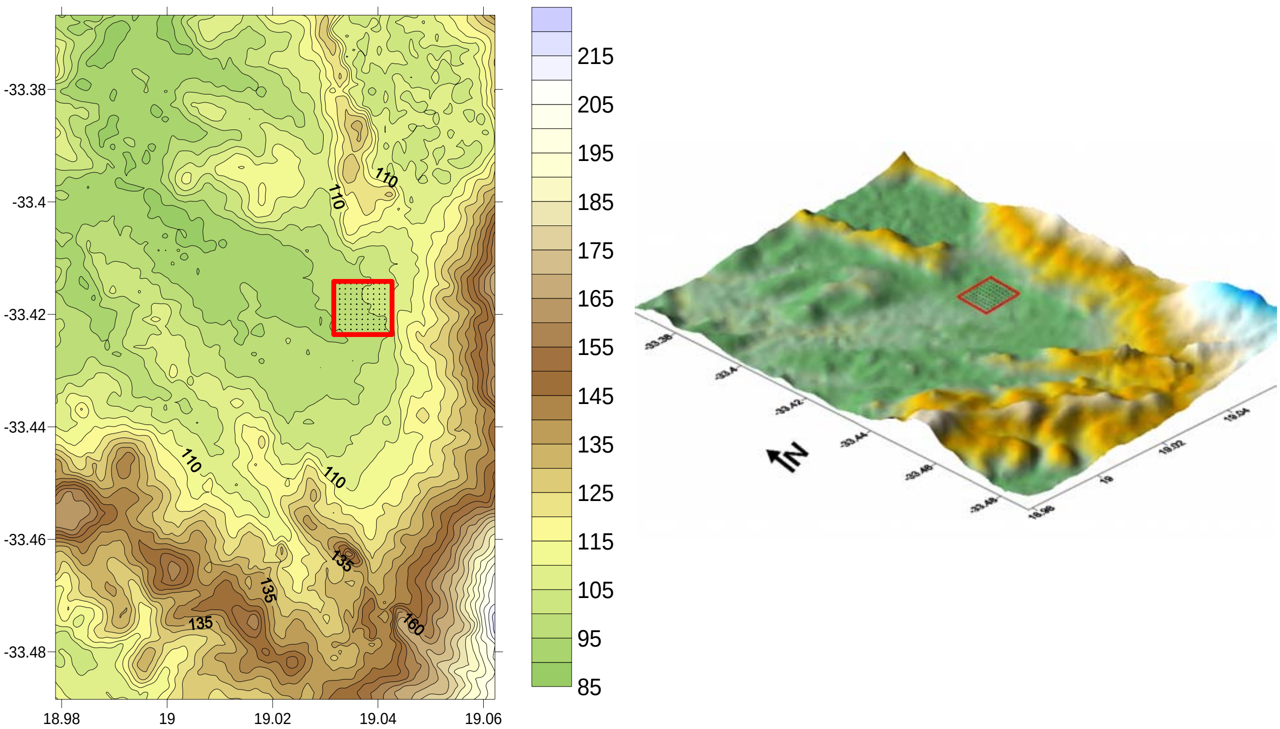


Figure 182 Topography of the area around the observatory #32 Elandsberg (red square) (derived from SRTM-dataset, height in m asl)

The observatory comprises a homogenous plain structure with a mean height of approx. 100 m asl and a slight inclination towards the west. The topography is nearly flat with a total of 4 m height difference in the observatory. Few small drainage lines or creeks dissect the area in various directions following the microtopography. The entire area drains via the Bergrivier towards the west and northwest.

The substrates of the observatory differ from the direct shale derived soils in the western adjacent areas, probably one reason for the former exclusion of this part from agriculture activities. The stratigraphy is characterised by quaternary substrates of different origin comprising clayey shale debris, pebbles and larger fragments of different origin with signs of fluvial transport. Additionally, a quartz rich, sandy substrate is often found as a top layer. Prominent features in the structureless landscape are small mounds with sandy material of a few metres in diameter. Most likely, these mounds are a result of burrowing animals.

The vegetation can be described as Renosterveld, a shrubland vegetation type belonging to the Fynbos of the Cape Floral Kingdom. The naming follows the typical Renosterbos (*Elytropappus rhinocerotis*). The combination of a nutrient poor substrate and periods of water logged conditions also provide a habitat for several sundew species. Two habitats were distinguished in terms of vegetation aspects: i) low vegetation, which can be assigned to the Swartland Alluvium Fynbos and ii) the typical renosterbush vegetation.

3.18.3 Soils

3.18.3.1 Main soil units

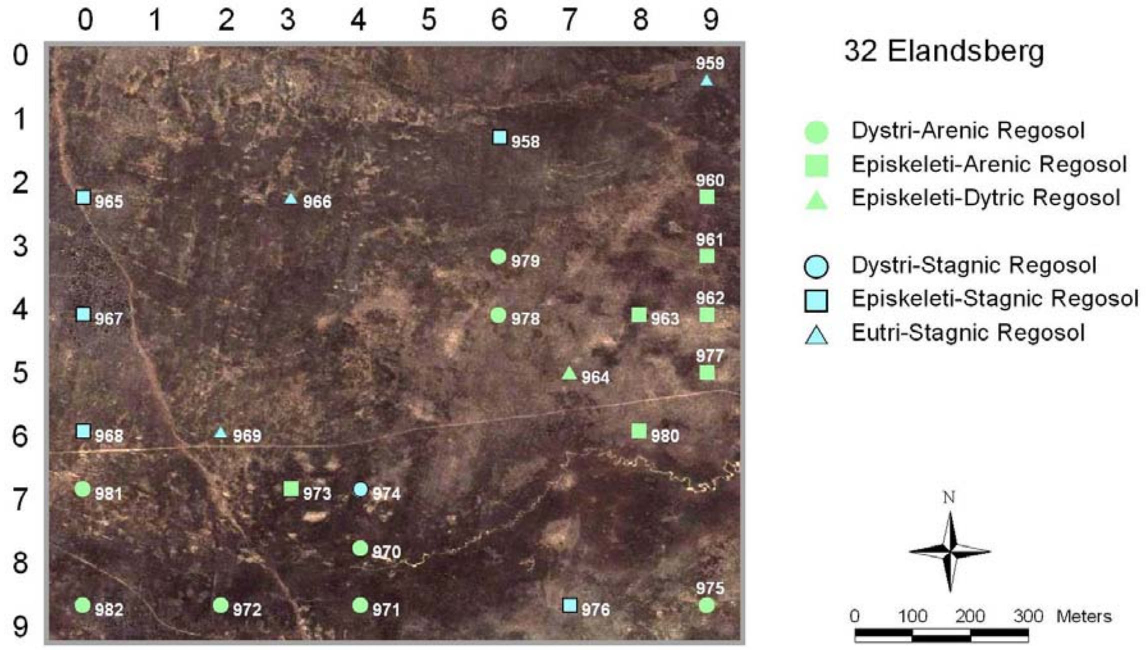


Figure 183 Distribution of soil units (WRB 1998, 2nd qualifier level) on the observatory #32 Elandsberg (Ranking 1-25)

According to the WRB (1998) Regosols are the only reference group found on the observatory (see Figure 183 and Figure 184). A more detailed classification is possible by using the qualifier ‘stagnic’, which indicates water logged conditions over a period of time. Such conditions are evident for a number of profiles. By including the texture, the content of fragments and the base status the soils were further specified. Except for a dominance of Stagnic Regosols in the north and northwest, no clear spatial pattern of soil units on the observatory is detectable. Differences in miocrotopography and soil properties over short distances lead to a scattered distribution of the several soil units. Regosols with a sandy texture in the upper section of the profile are the most common soil unit, which typically are underlaid by a shale derived, denser and more clayic horizon.

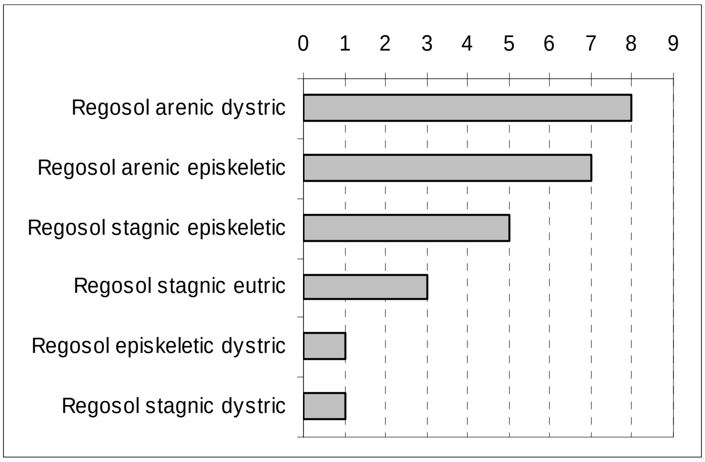


Figure 184 Frequency distribution of WRB soil units (1998, 2nd qualifier level) on the observatory #32 (Elandsberg)

3.18.3.2 Remarks on classification

The classification of the soil units is provided in the WRB (1998) nomenclature. The most important features and the differences of these soils (stagnic properties, fragments, texture, and base status) could be described sufficiently with the used qualifiers. However, problems occur in the case of very sandy topsoils, which lack specific signs of stagnic properties and are thus not allowed to be specified as stagnic. This lack is a typical feature of quartz rich substrates under water logged conditions which can be assumed for these Arenic Regosols as well.

The application of the new version of the WRB (2006) reveals only minor changes. The newly introduced qualifiers ‘clayic’ and ‘siltic’ allow a more precise characterisation of the texture in some profiles.

3.18.3.3 Description of selected reference profile

Reference profile # 1

Profile: **959**	Ha: **09**	Classification (WRB 1998) **Eutri-Stagnic Regosol** (WRB 2006) **Stagnic Regosol (Eutric, Clayic)**

cm	Horizon	Description
0–10	Ah	Medium Sand (mS), 23% fragments, single grain structure, dark grey, Munsell 2,5Y5/2 dry and 2,5Y3/2 moist, >50 roots/dm^2, low excavation difficulty
10–30	Bw1	Medium Sand (mSfs), 35% fragments, single grain structure, yellowish grey, Munsell 2,5Y6/4 dry and 2,5Y4/4 moist, 25 roots/dm^2, moderate excavation difficulty
30–50	Bwt1	Sandy clay (Ts3) with medium Sand (mSgs), 10% fragments, angular blocky structure, yellow-ochre, Munsell 2,5Y6/6 dry and 2,5Y5/6 moist, 15 roots/dm^2, high excavation difficulty
50–60	Bwt2	Silt loam (Us) with medium Sand (mS), 15% fragments, massive structure, strongly calcareous, light ochre, Munsell 2,5Y7/5 dry and 10YR6/5 moist, 5 roots/dm^2, high exc. difficulty

Figure 185 Description of profile 959

The Eutri-Stagnic Regosol of Figure 185 is a typical example for soils that typically consist of two strata. A sandy top layer up to a depth of 30 cm contains around 30 % coarse gravel with signs of fluvial transport. Below, with a sharp border, a slightly calcareous, dense sandy clay layer with less fragments occurs. Fe and Mn concretions in this layer and the bleached character of the topsoil indicate hydromorphic dynamics in form of water logging.

The $EC_{2.5}$ of 15 µS cm^{-1} in the second horizon indicates the extremely low nutrient status. The slightly acid pH-value increases to neutral in the subsoil horizon, which contains > 2 % inorganic carbon. Organic carbon decreases strongly with depth from 1.2 % in the topsoil. The C/N ratio of 20 in the topsoil indicates a typical acid environment with reduced biological activity and litter with high C/N ratios.

The change in substrate is clearly shown by the strong increase of total element contents and the TRB increasing from 10 in the quartz rich sand up to 100 - 400 cmol$_c$ kg^{-1} in the calcareous, shale derived layer. The content of water-soluble ions is extremely low with 1-5 mmol$_c$ kg^{-1} from top to subsoil, while the high values in the AM-extractable bases of the subsoil are a result of carbonate dissolution.

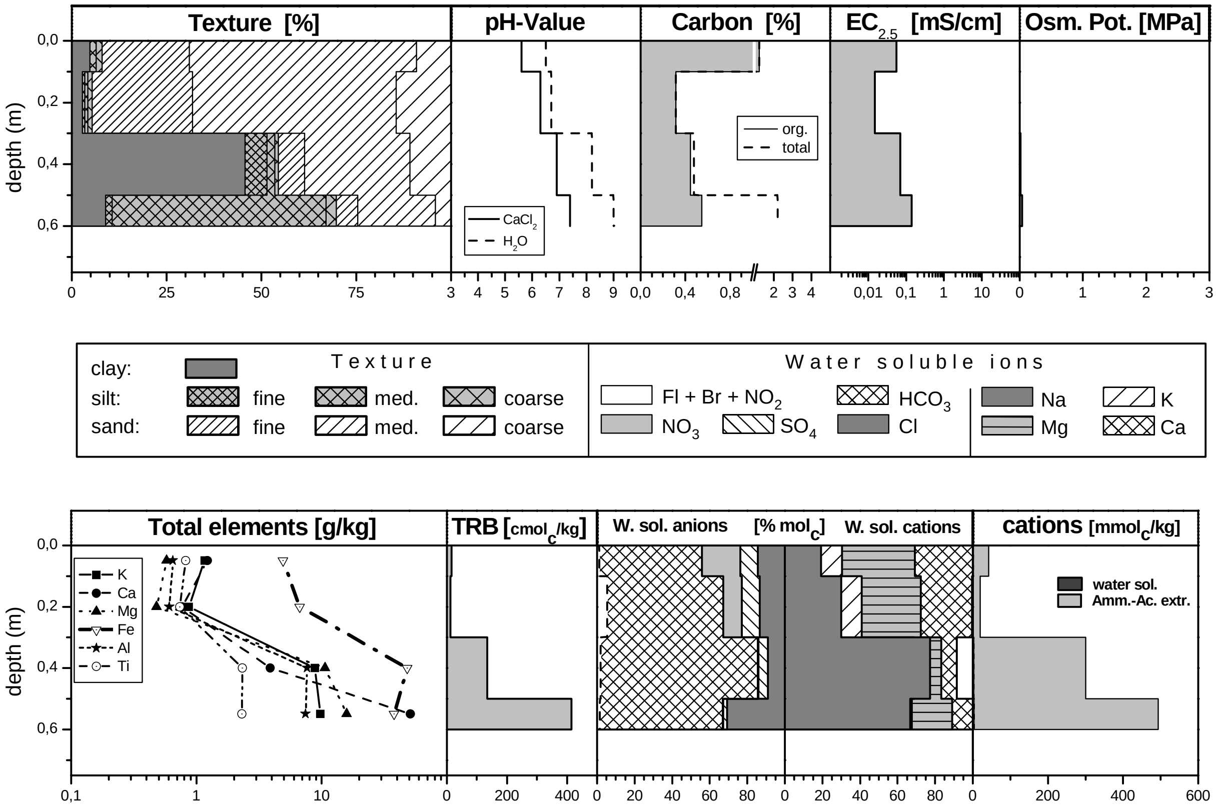


Figure 186 Properties of profile 959

3.18.3.4 Discussion of soil properties

Figure 187 depicts the variability of selected soil properties in three different depth intervals based on data of 25 profiles. Except for organic carbon, the parameters show only small ranges and low median values in the topsoil characterising the sandy and nutrient poor, acid environment. Depending on the thickness of the cover stratum, median values and ranges increase in subsoil (except for OC). The rooting space (RS) shows high variations caused by infrequently underlying bedrock and profiles with high contents of coarse fragments. However, the median of > 60 % indicates a relatively deep RS.

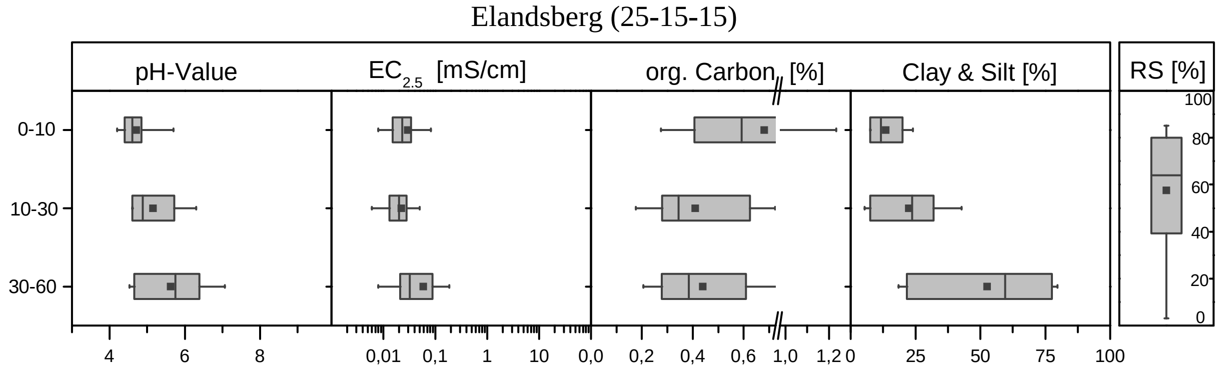


Figure 187 Variability of selected soil properties in three depth intervals for the observatory #32

Box = 25-75 % with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

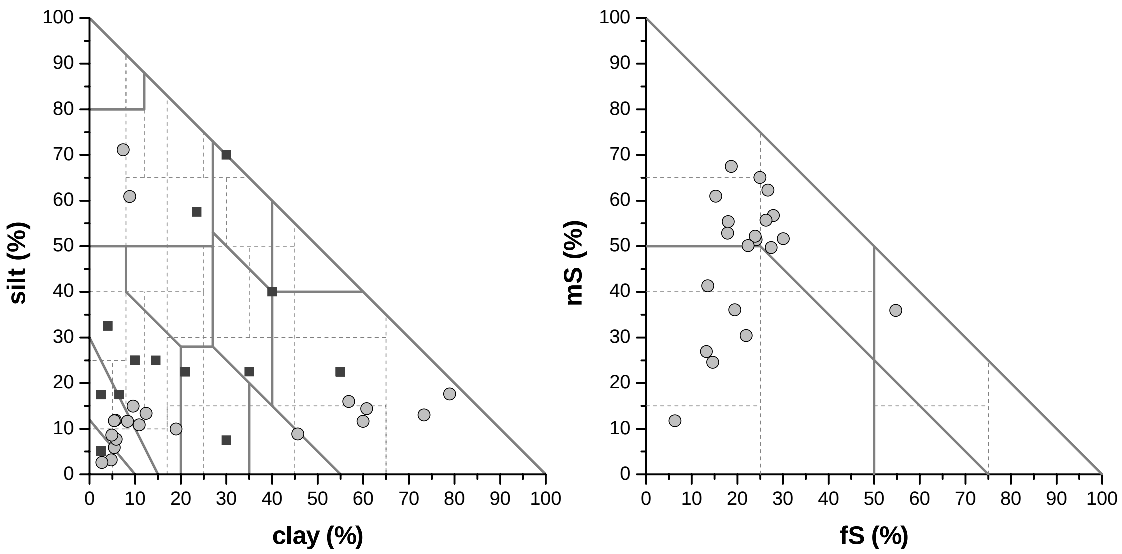


Figure 188 Results of the texture analyses for the observatory #32 Elandsberg

squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 188 shows the results of the texture analyses of all samples for the observatory #32. Depending on the strata, a wide range of sand-, clay- or silt-dominated textures occur. With regard to the sand fractions, the samples cover a range from coarse sands as a component of the shale influenced strata to medium sand as the dominant fraction of the alluvial cover sandy substrate.

Pattern analogies in the soil and vegetation distribution are not analysed yet but are at least evident on different scales with respect to the water logging status. The depth of the underlying shale-derived materials with higher base and nutrient status is suspected to play an additional role on the extremely nutrient-poor, sandy topsoil.

3.19 Observatory 33 Cape Peninsula National Park

3.19.1 Regional overview

The observatory #33 (Cape Peninsula NP / Cape of Good Hope) is located on the Cape Peninsula in the Table Mountain National Park (TMNP) south of Cape Town. The Peninsula with an area of 470 km^{-2} is home to 2285 plant species with 90 species endemic to the Peninsula. It is globally regarded as an important hot spot of biodiversity (Cowling et al. 1996, Myers 2000, Linder & Hardy 2004, Linder 2005). The typical vegetation is Fynbos, a fine leaved, sclerophyllous and fire-prone shrubland or 'heathland' vegetation associated with low nutrient substrates and summer drought (see also Richards et al. 1997, Cowling et al. 1996, Cowling & Lombard 2002).

The Peninsula is subject to a mediterranean climate, characterised by cool, moist winters and warm, dry summers. Mean annual rainfall on the Peninsula varies considerably from 2270 mm on the table Mountain to only 402 mm at the Cape Point (Cowling et al 1996).

The region is characterised by high topographical heterogeneity resulting in strong differences in mean annual precipitation. In combination with a high variety in lithology, this results in long, steep environmental gradients comprising a high number of (micro-) habitats.

Prominent feature of the landscape is the scenic arrangement of Atlantic Ocean mountainous areas with massifs and plateaus comprising sandstones partly covering the Cape Granite Suite. Geologically, this region belongs to the Table Mountain Group with the Peninsula formation characterised by quartzite sandstone. A phenomenon not yet understood regarding the Fynbos ecosystem is how it manages to support abundant and diverse vegetation on generally nutrient-poor bedrock, especially the quartz arenite of the Peninsula Formation sandstone (Cowling et al. 1996).

The vegetation of the southern part of the Peninsula where the observatory is situated, the Peninsula Sandstone Fynbos, is part of the Southwest Fynbos bioregion (Mucina & Rutherford 2005), accompanied by smaller areas of Sand Fynbos and Strandveld vegetation. Characteristic species are of the Ericaceae, Proteaceae, Asteraceae and Restionaceae families and show high levels of diversity and endemism.

Natural periodic fires are of high importance for the dynamic of the natural vegetation within the TMNP as a trigger for the renewal and succession of the vegetation. This impact is well visible on the observatory, which is located in the southern part of the TMNP. The open, whitish zone in the southwest of the observatory is a consequence of a fire in 2002 (see Figure 189). Grazing impact by game occurs, but is considered to be of insignificant impact. A major threat for the unique flora of the northern part of the Peninsula is the pressure by agriculture and urbanisation combined with the spreading of invasive alien plants (RICHARDSON 1996). The latter is also a threat for already protected areas like the Cape of Good Hope where the BIOTA observatory is situated.

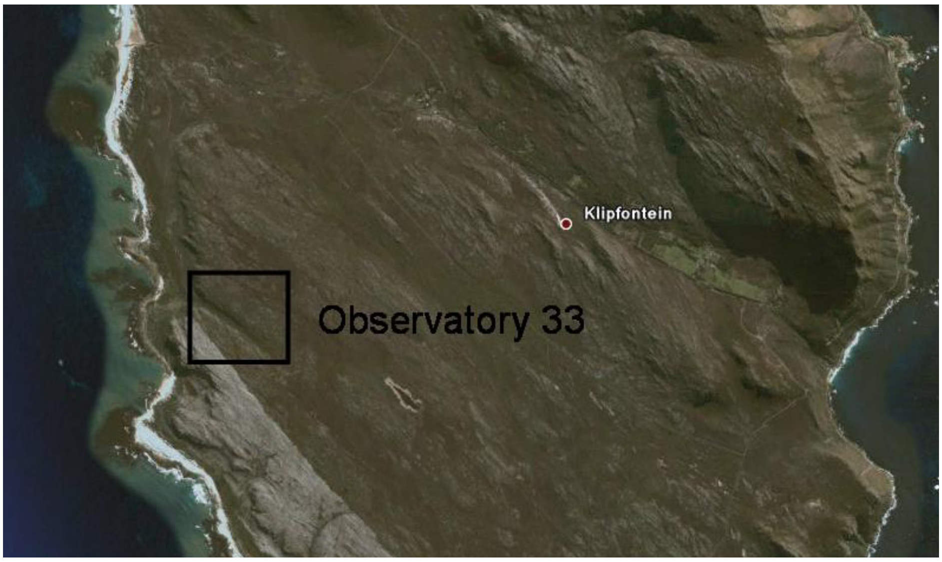


Figure 189 Location of the observatory #33 on the Cape Peninsula at Olifantsbos

3.19.2 Observatory description

The observatory is located approx. 10 km north of Cape Point at the west coast in the protected area of the TMNP. The locality is known as Olifantsbos. The landscape comprises a low sandstone plateau dissected by a few drainage valleys draining towards the western coast. Within the observatory, mean height is around 100 m asl with the highest area (113 m asl) in the northeast. The area is generally flat except for the northwestern part, which is characterised by a small valley with a periodical creek and lowest positions around 63 m asl. Mean annual rainfall is around 400 mm (recorded at Cape Point).

The coarse weathered sandstone soils are drained regularly and extensively. However, in combination with the underlying, massive bedrock, building some low structured subterranean ridges, drainage on some areas is impeded resulting in waterlogged conditions in the wet winter months. This is reflected by a basic distinction of the vegetation into a proteoid Fynbos on the well drained sites and a restioid Fynbos on the seasonally waterlogged sites. Waterlogged conditions predominantly occur in the northeast and the southeast of the observatory clearly visible on the satellite image indicated by a browner colour of the vegetation aspect and less arenite outcrops (Figure 192). Although these parts are the highest within the observatory, water logging occurs due to the presence of sandstone barriers in the ground that pose an obstruction and thus cause shallow waterlogged or even flooded basins. A small seasonal creek drains the area of the observatory towards the valley in the northwest.

During fieldwork in October 2005 (end of the rainy season), waterlogged conditions on the observatory and drainage by the creek was evident. Figure 191 depicts the aspect of the waterlogged profile and of two dominant Fynbos units. A photograph of the small creek documents the high content of dissolved organic carbon (DOC) in the drainage water of the area.

An additional important feature of the observatory is the heterogeneous structure of the underlying sandstone resulting in a small-scale pattern of outcrops, especially in its western part. Besides this clearly visible feature, the heterogeneity is also manifested in small scale soil pockets and small depressions with waterlogged conditions during the winter.

As a typical dynamic feature of the Fynbos, the most southwestern part of the observatory experienced a bush fire in 2002, which burned down the vegetation completely. In Figure 190, the two current aspects along the fire-borderline are shown. On the left hand side, the proteoid Fynbos still exists, while on the right hand side a three-year old succession stage has been established on the burned site. For the ranking procedure, only two habitats were distinguished: burned and unburned habitat.

Figure 190 Typical aspect of proteoid Fynbos (left) and area 3 years after the fire (right)

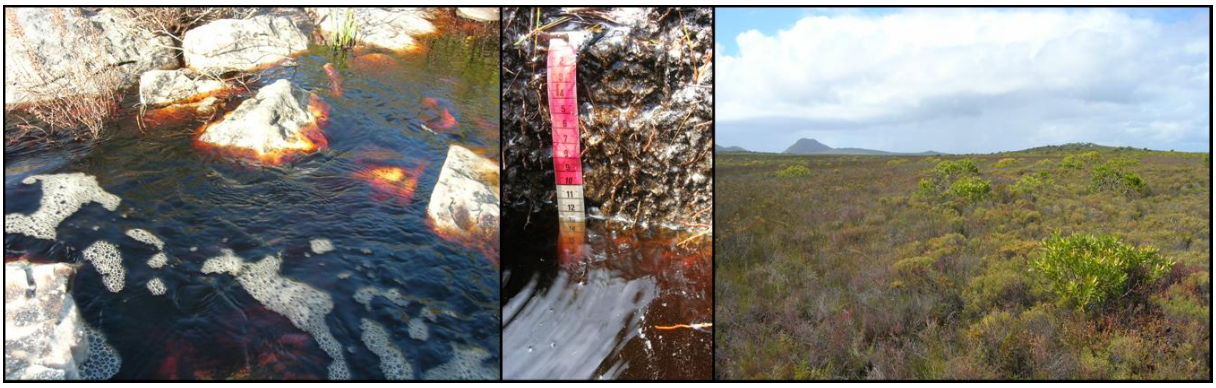


Figure 191 DOC in form of fulvic acids in the creek (left), fulvic acid water in water logged profile (centre), typical transition from restioid fynbos to proteoid fynbos by change in water dynamics (right)

3.19.3 Soils

3.19.3.1 Main soil units

25 soil profiles were examined by means of the standardised ranking procedure. Position and classification of these profiles are provided in Figure 192. In Figure 193, the frequency of these soil units on a two-qualifier level of the first 25 ranking priorities is provided.

According to the WRB (1998), the reference groups Podzol and Leptosol are found. The latter are restricted to the shallow outcrop regions of the arenite sandstone, whereas all the other profiles are classified as Podzols. The most frequent soil unit is the episkeletic Podzol mainly found in the central and southwestern part of the observatory, followed by the gleyic Podzol in the eastern part of the observatory. Here, the basin-like structure of underlying sandstone impedes drainage and deeper percolation of the water. As a result, seasonal gleyic conditions occur during the winter months. These conditions are found on wider areas in the eastern part of the observatory, but infrequently also occur in other parts of the observatory where similar microtopographic features are evident on a smaller scale.

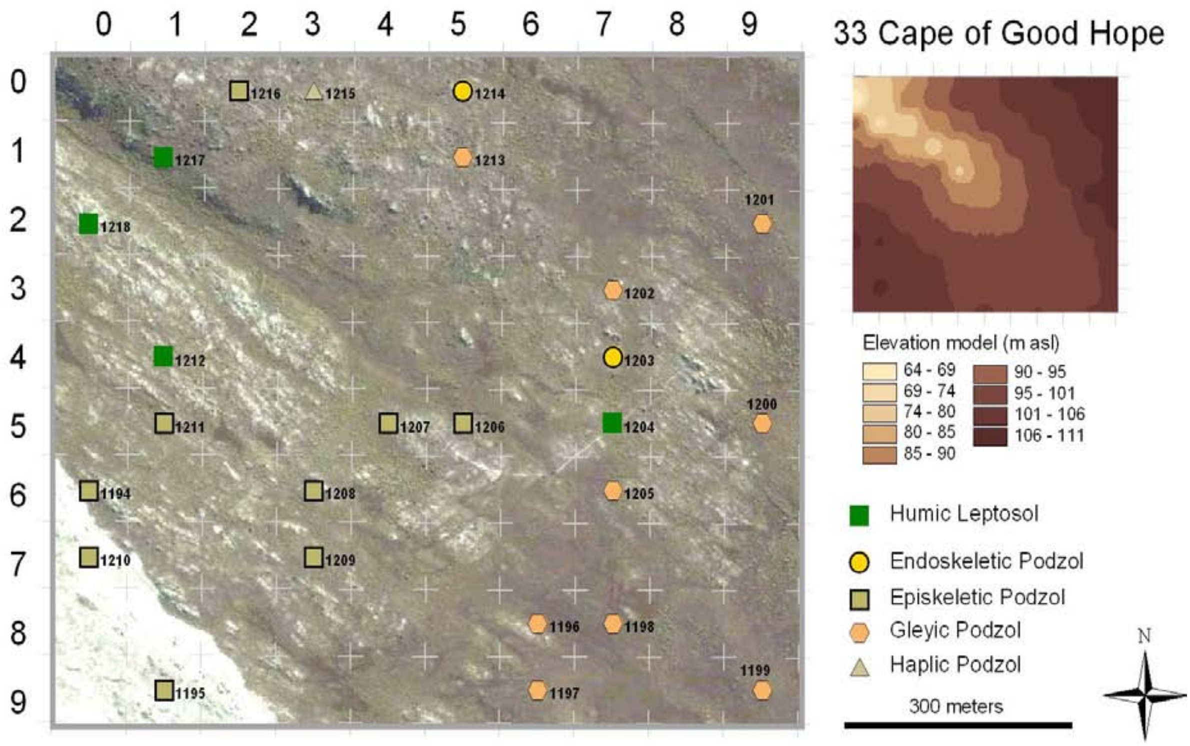


Figure 192 Distribution of WRB soil units (1998, 1st qualifier level) on the observatory #33 Cape of Good Hope / Cape Peninsula

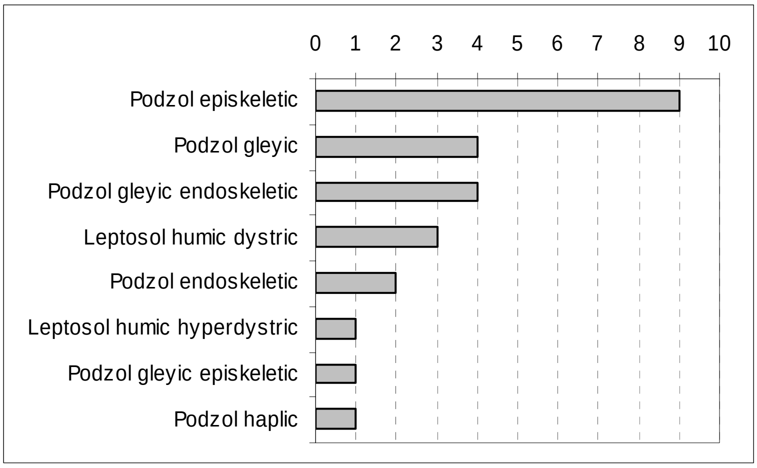


Figure 193 Frequency distribution of WRB soil units (1998, 2nd qualifier level) in observatory #33 (Cape of Good Hope / Cape Peninsula NP)

3.19.3.2 Remarks on classification

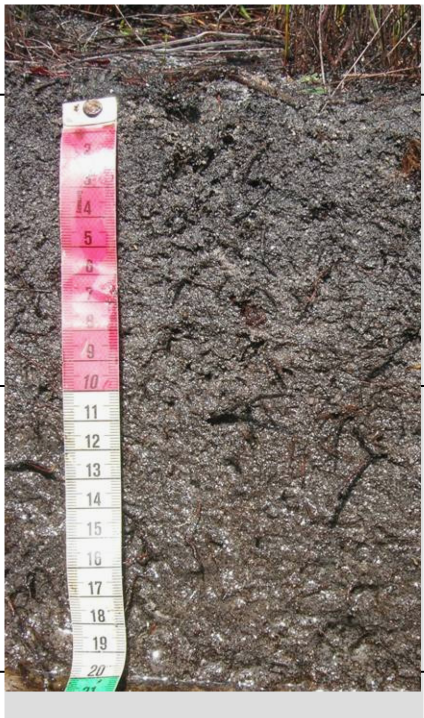
The classification of the soil units is provided in the WRB (1998) nomenclature. The most important features of these soils (leaching processes with fulvic acids, seasonal waterlogging, content of coarse fragments and depth of bedrock) could be described sufficiently with the applied qualifiers and reference groups. However, the application of the qualifiers as well as the chose of the reference group of Podzols is based on some assumptions and observations during the field survey. The diagnostic spodic horizon (represent accumulation of translocated organic acids, iron and aluminium) has only been found in form of organically enriched weathered rinds of the sandstone material. This lack of diagnostic horizon should normally lead to the classification as i) Arenosols in case of the deeper profiles, and ii) as Regosols for the profiles of medium depth. Colour requirements for albic horizon are also only partially fulfilled. However, due to the evidence of strong leaching and translocation of dissolved organic carbon (DOC) observed in the drainage water and transported further into the ocean, I decided to express this character with the reference group Podzols. Another subjective decision is the use of the qualifier ‘gleyic’ to characterise the waterlogged conditions in some of the profiles leading to a distinct vegetation pattern. The required reductimorphic colours are hardly identifiable due to the overriding influence of organic matter (DOC) influence as well as the very low content (or absence) of colouring agent such as iron and manganese. An additional minor restriction is that it is not possible to assign the leached character in the shallow Leptosols.

The application of the new version of the WRB (2006) reveals one important change. Due to the newly introduced qualifier ‘leptic’ in the reference group Podzols it is possible to characterise the shallow character without changing the reference group from Podzol to Leptosol. This enables to change Humic Leptosols into Leptic Podzols. For slightly podzolic Leptosols it is also possible to use the new qualifier ‘greyic’.

3.19.3.3 Description of selected reference profile

Reference profile # 1

Profile: **1196**	Ha: **86**	Classification (WRB 1998) (WRB 2006)	**Episkeleti-Gleyic Podzol** **Gleyic Podzol (Episkeletic)**



cm	Horizon	Description
0–10	Ah	Medium sand (mS), single grain to subangular blocky structure, dark grey, Munsell 10YR4/1 dry and 10YR3/1 moist, 21-50 roots/dm^2, strongly moist, low excavation difficulty
10–20	Bg	Medium sand (mS), single grain to subangular blocky structure, grey, Munsell 10YR5/1 dry and 10YR3/1 moist, 21-50 roots/dm^2, wet, low excavation difficulty
20–21		85% fragments, grey, wet

Figure 194 Description of profile 1196

The Episkeleti-Gleyic Podzol of Figure 194 is a typical example for the seasonally waterlogged profiles in the eastern part of the observatory. During the survey in September 2005, the water level in the profile was 10 cm below the soil surface. Below a 20 cm thick layer of sand occurs the transition to the underlying sandstone with high contents of coarse fragments.

The sandy texture consists predominantly of medium sand. The very strongly acid pH-value and the $EC_{2.5}$ of around 50 µS cm^{-1} are nearly constant with depth. Organic carbon decreases from 2.0 to 1.5 % in the second horizon. Both horizons show wide C/N ratios of 27-30.

The analyses of total element contents revealed the nutrient poor character of the sandstone derived materials. Almost all of the elements are below the detection limit. The same is true for the extremely low contents of water-soluble ions as well as the AM-extractable ions (not shown here).

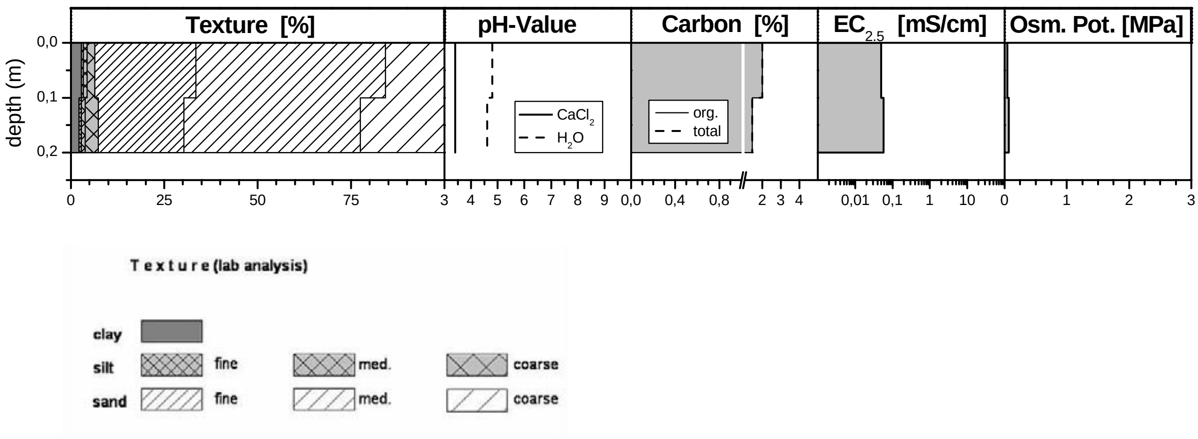


Figure 195 Properties of profile 1196

Reference profile # 2

Profile: **1210**	Ha: **70**	Classification (WRB 1998)	**Episkeletic Podzol**
		(WRB 2006)	**Haplic Podzol (Episkeletic)**

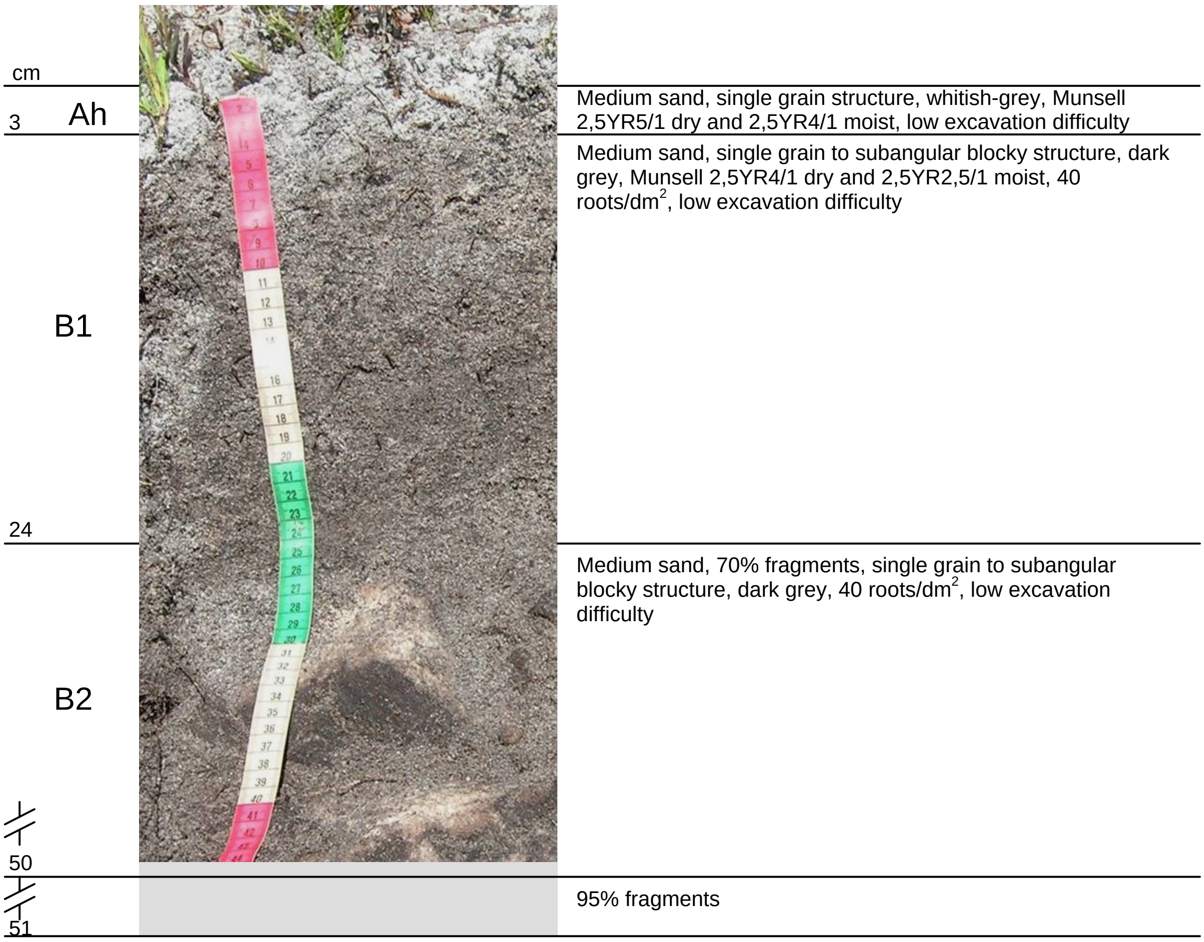


Figure 196 Description of profile 1210

The Episkeletic Podzol of Figure 196 is a typical example for the drier Podzols profiles in the western part of the observatory. Except for the water logging, the profile morphology with a sandy layer of 20 cm thickness, overlying a fragment-rich transition zone to the arenite layer, is comparable to the previously described profile. However, drainage is favoured by stronger fragmented bedrock or the lack of bedrock barriers. A prominent feature of these drier Podzols is a thin topsoil horizon, which is more strongly bleached than the underlying horizons. Additionally, the contents in silt, clay and organic carbon are reduced. The thin horizon is probably of aeolian origin, i.e. translocated bleach sand of burned, open areas. Although fulfilling the requirement for an albic horizon, it should be noted that this can not be the single source of organic components in the subsoil.

The sandy texture of the profile consists predominantly of medium sand. The moderately acid pH-value and the $EC_{2.5}$ of around 12 µS cm^{-1} are nearly constant with depth. Organic carbon reaches values of 2.6 % in the second horizon. Both horizons again show wide C/N ratios of 27. Similar to the previous profile, the analyses of total element contents revealed the nutrient poor character of the sandstone-derived materials. Almost all of the elements appear below the limit of detection. The same is true for the extremely low contents of water-soluble ions as well as the AM-extractable ions (not shown here).

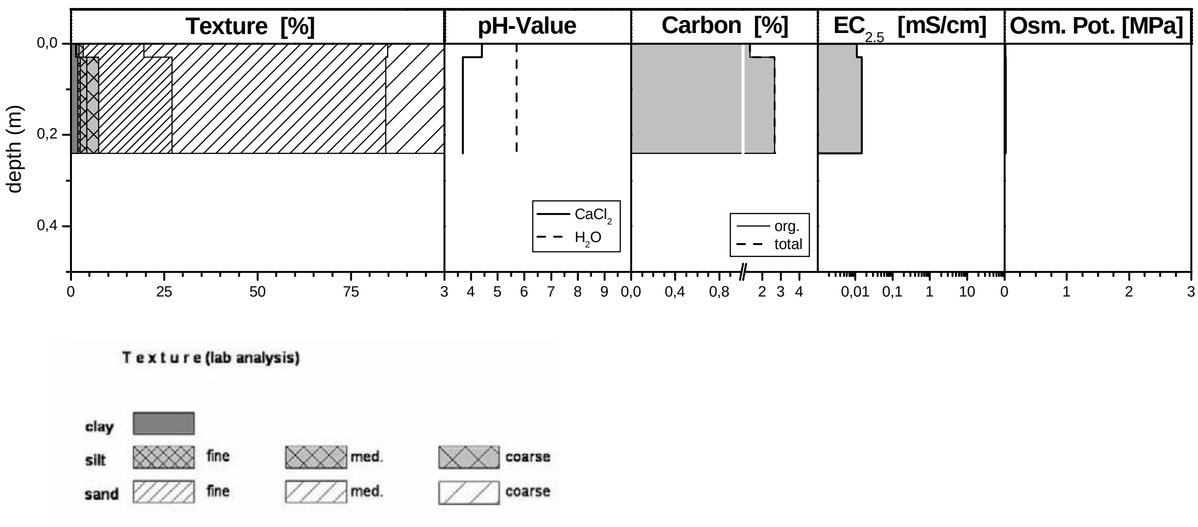


Figure 197 Properties of profile 1210

3.19.3.4 Discussion of soil properties

Figure 198 depicts the variability of selected soil properties in three different depths intervals based on the data of 25 profiles. The pH-values and the $EC_{2.5}$ show very low median values and low ranges characterising the overall acid and nutrient poor conditions of the observatory. Fine earth texture is characterised by the dominant sand, except for one outlier profile with loamy sand. Organic carbon and the rooting space (RS) show the highest variability of selected parameters with wide ranges from 1 % up to 10 % organic carbon and RS from 5 % to 100 %.

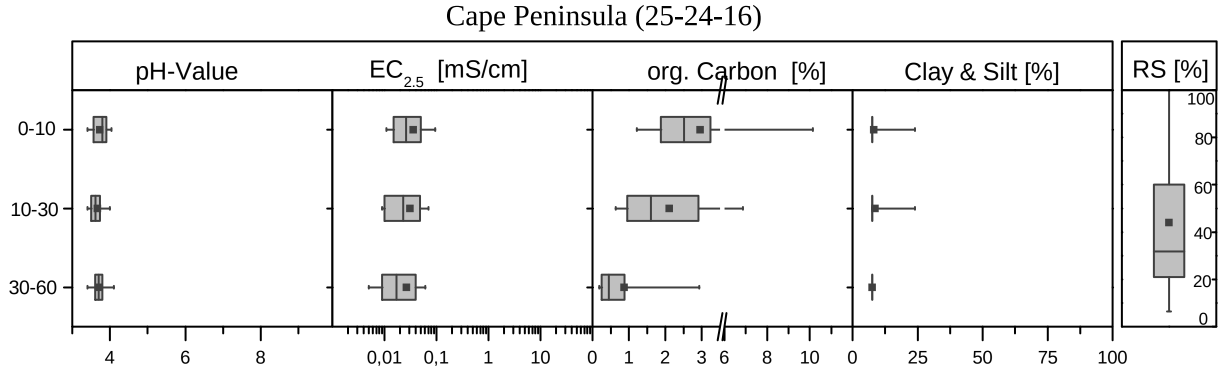


Figure 198 Variability of selected soil properties in three depth intervals for the observatory 33

Box = 25-75% with Median (line) and Mean (point), Whisker = Min/Max. Numbers in brackets indicate the number of samples in each depth (top → down), RS = rooting space

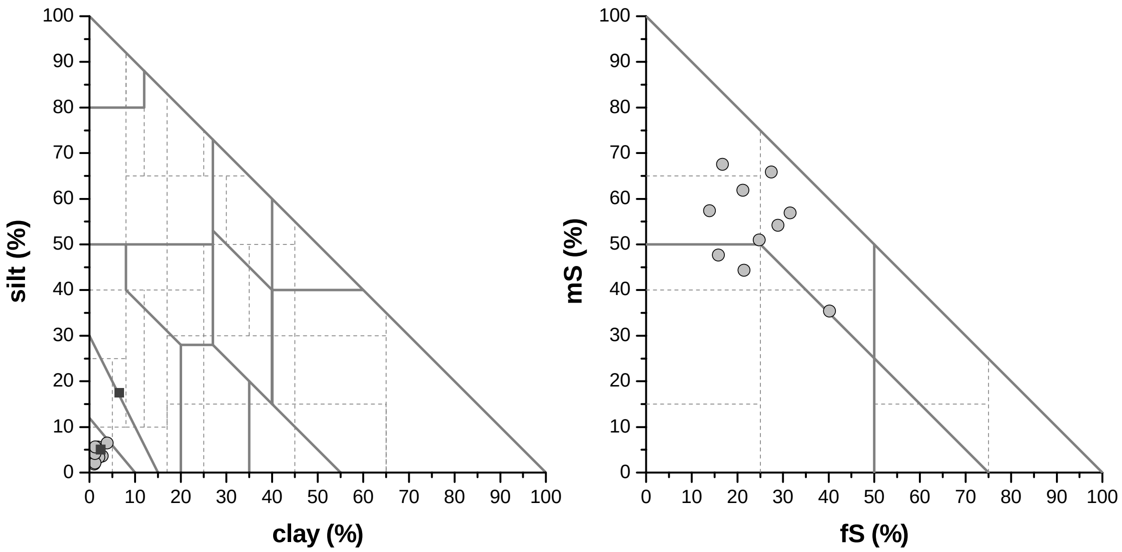


Figure 199 Results of the texture analyses for the observatory 33 (Cape Peninsula)

Squares = finger test (all samples) and circles = lab analyses (selected samples)

Figure 199 shows the results of the texture analyses for all samples from the observatory #33. The texture is pure sand with nearly no silt and clay percentage. With regard to the sand fractions, the analysed samples are predominantly medium sands (mS) with varying contents of fine and coarse sand.

Pattern analogies in the soil properties and vegetation distribution on the observatory are most evident in the distinction between a restioid Fynbos on the waterlogged sites in the eastern part of the observatory and a proteoid Fynbos on the drier habitats. Besides this large-scale pattern, small-scale topography within a few metres reveals a similar pattern.

The analyses confirmed that especially the waterlogged profiles have slightly higher EC values compared to the dry habitats. This may be a result of a soluble salt input with drainage water, which predominantly flows laterally in the soil originating from the surrounding areas.

4 Concluding discussion and remarks on the soil inventory along the transect

The description of the selected observatories in the previous chapters offered a detailed overview of the individual sites. This chapter summarises the results of the WRB classification as well as the parametric behaviour of selected soil properties by focussing on the overall pattern of soil units and selected soil properties. This enables both, the overview of the predominant soil units and the comparison of the variability of soil properties along the transect.

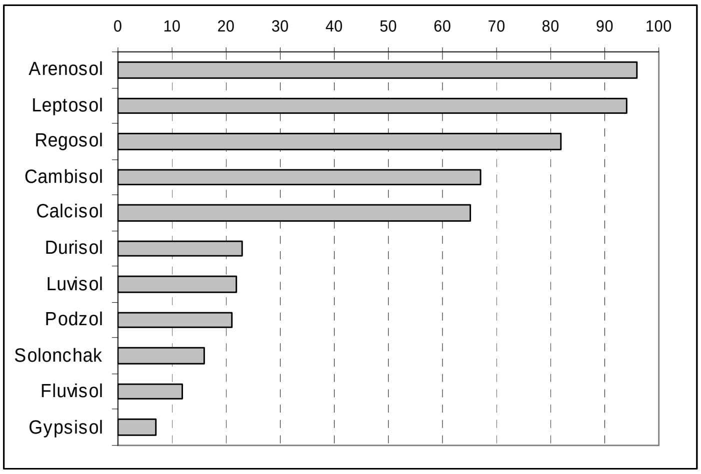


Figure 200 Frequency of occurrence of soil reference groups (WRB 1998) along the transect

Figure 200 gives an overview of the frequency of the occurring soil reference groups - the broadest level of classification - along the entire transect. The great variety is highlighted by the occurrence of 11 out of 30 reference groups (in WRB 1998, 32 in WRB 2006 respectively) possible in the worldwide valid system. Two major groups can be distinguished: i) Arenosols, Leptosols, Regosols, Cambisols, and Calcisol recorded with 65 – 95 cases each and ii) the group of Durisols, Luvisols, Podzols, Solonchak, Fluvisol and Gypsysols recorded with only 7 – 22 cases each. Due to the subjective selection of observatories and subsequent substrate dominances, this overview cannot provide a representative pattern of the occurrence of reference groups in the entire study area, but shall summarise the results for the transect. Calcisols for instance show a relatively high abundance which is caused, however, by the regional setup of the observatories #39 and #40 in a calcrete-dominated landscape, while on the remainder of the transect Calcisols occur only sparsely. Also, the relatively high number of dune sites (5) in the observatories favours the dominance of Arenosols. High Leptosol numbers are achieved due to a high number (5) of observatories in mountainous regions of the escarpment, especially in South Africa. Few reference groups occur exclusively in individual observatories such as Gypsisols, which are prominent on observatory #16, near the coast, and Podzols occurring on the Cape Peninsula. These examples illustrate that regional aspects strongly affect the frequency of reference groups. The same is true when looking at the soil unit level. Here, the frequencies of soil units clearly show a lognormal distribution with few dominant units such as Dystri-Ferralic Arenosols and Epipetric Calcisols with 25 – 35 cases. A strong decrease in occurrence reaches the level of 1 individual per soil unit for approx. 55 % of all occurring soil units (see Figure 201).

The WRB system revealed a good sensitivity for soil classification on the applied scale of 1 km^2. For the majority of the observatories it was revealed that the major differences in soil properties could be expressed satisfactorily. The newly introduced qualifiers in the revised version (FAO 2006) enhance this sensitivity, especially due to the improved expression of texture properties by clayic and siltic qualifiers for most of the reference groups. Also the newly introduced rule of differentiation of the qualifiers in prefix and suffix enhances the understanding. At the same time, this raises the necessity to apply all possible qualifiers with respect to a precise characterisation. The WRB 1998 still implies the application of hierarchical levels when using different qualifier numbers.

The options to express salinity in the classification of WRB (2006) are also enhanced with respect to lower requirements regarding the salinity status or its calculation, respectively. However, it is still not possible to express lower degrees of salinity, which are of strong ecological importance. Important for this study region is the new possibility to use the qualifier salic for Leptosols. It is now possible to distinguish shallow Leptosols by their salic attribute. Also very useful is the option to define Alkalic Cambisols to separate them from the neutral pH ranges. In the Podzols, the ‘hyperskeletic’ qualifier allows to express intergrades to Leptosols. The qualifier ‘puffic’ in the Solonchaks and ‘nudilithic’ for the Leptosols provide new options to separate ecologically different soils.

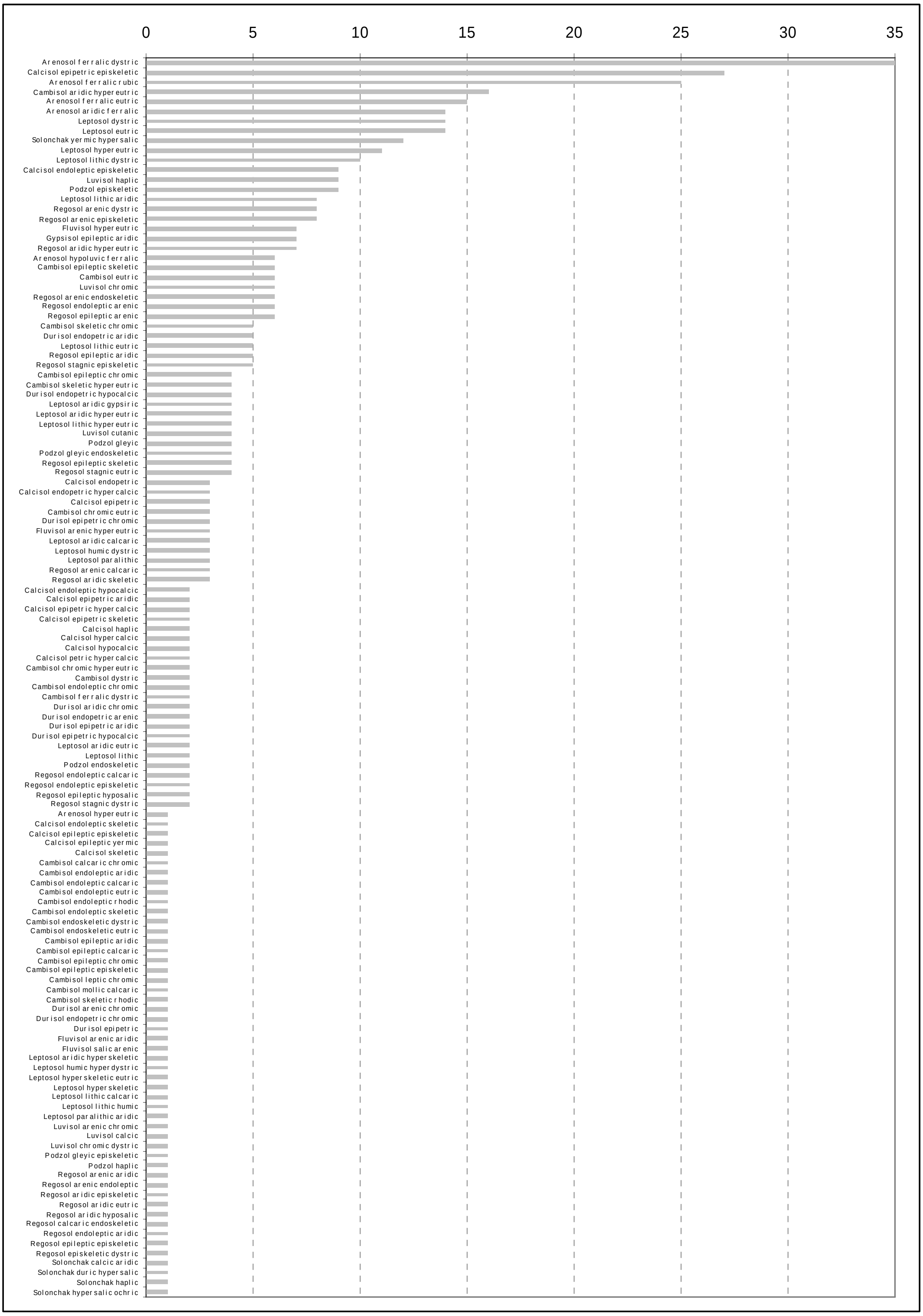


Figure 201 Frequency of occurrence of soil units (WRB 1998 2[nd] qualifier level) along the transect

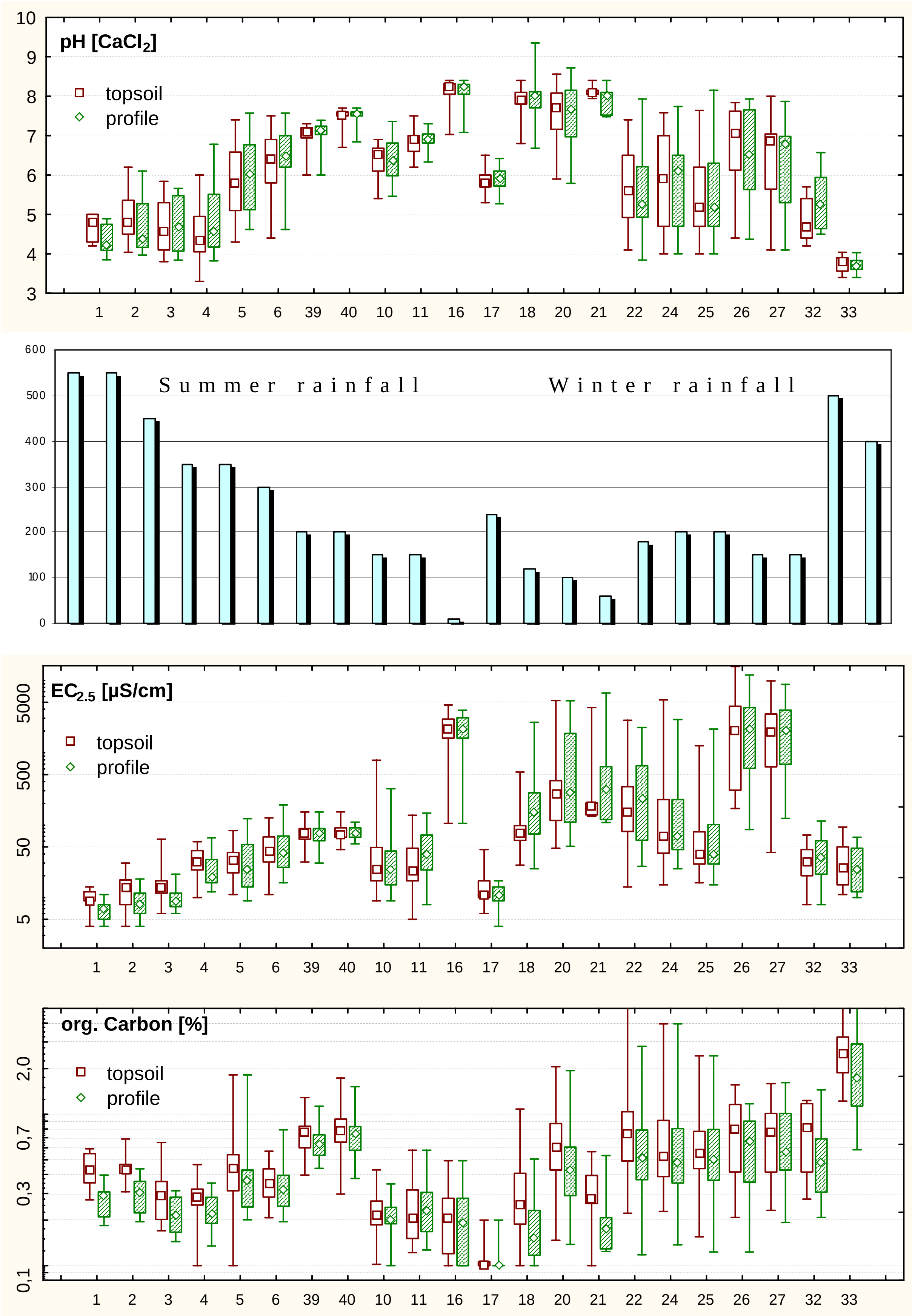


Figure 202 Soil properties and mean annual rainfall (mm) along the transect (Whisker = Min / Max, Box = 50 % of values)

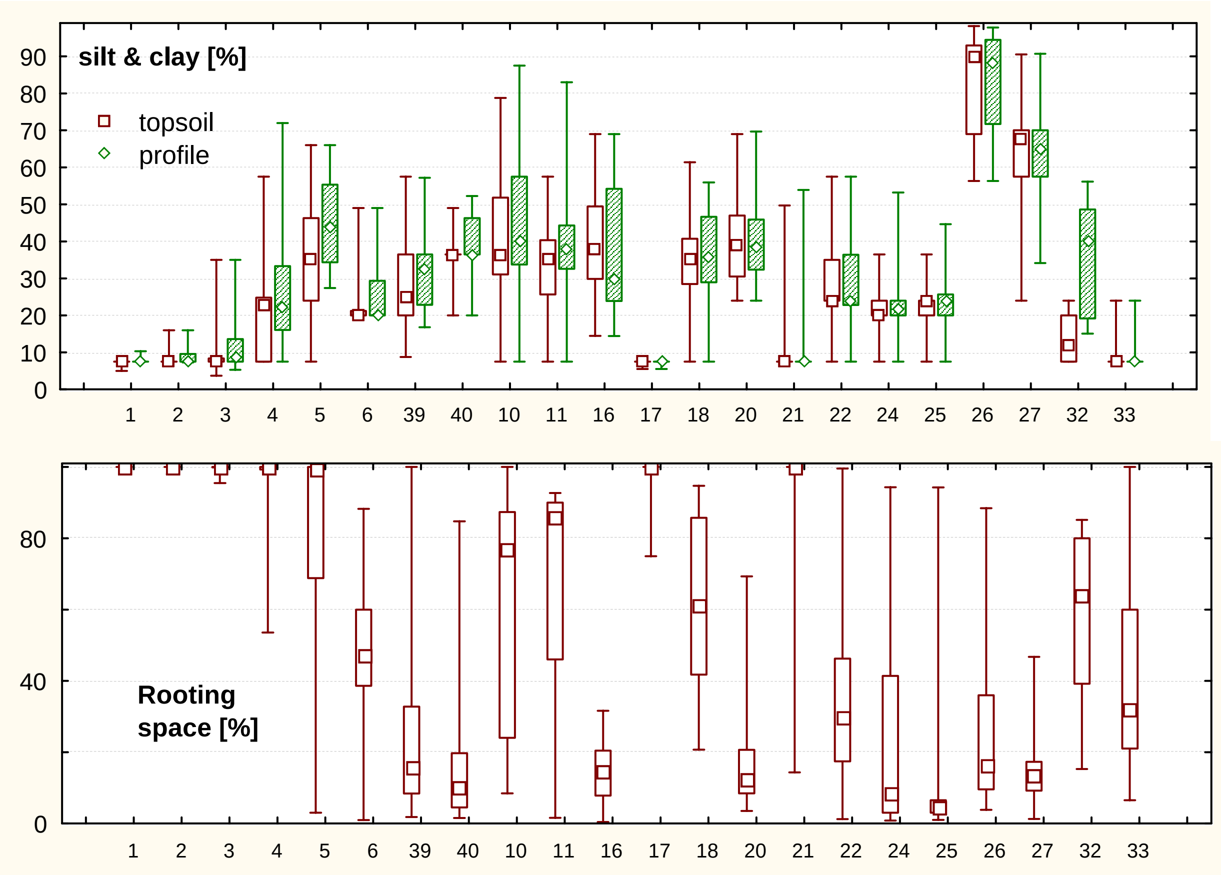


Figure 203 Silt & clay content and rooting space along the transect (Whisker = Min / Max, Box = 50 % of values)

Examples for the range and the variability of selected soil properties along the transect are provided in Figure 202 and Figure 203. The causes for the median values and the behaviour of the selected parameters are discussed in the previous chapters together with the single site descriptions. In the following, additional remarks on overall trends along the transect are provided. The explanation of trends cannot be discussed here in detail, as it requires an in-depth discussion of climate, substrate and land-use. Here, the focus shall be on the change of variability of selected parameters along the transect.

The most evident trend is shown in the **pH-value** and the EC. The pH-values show a reciprocal trend compared to the mean annual rainfall with a maximum variability in the central Namibian savanna and the winter rainfall dominated Namaqualand in southern Africa. The highest pH-values are found in the arid border zone between summer and winter rainfall (#18, #20, #21) and the costal desert site of Wlotzkasbaken (#16). Extraordinarily wide ranges of pH-values on the observatories #22-27 are caused by ancient termite activity and small scale patterns of salt accumulation. Additionally sampled small-scale transects revealed that on observatory #22 the higher pH-values are restricted to the areas of former termite nests (“Heuweltjies”), which show higher concentrations of calcium carbonate and soluble salts than the adjacent soils (PETERSEN et al. 2003). These accumulations seem to provide important ecological niches in this ecosystem.

The trend of the **EC** along the transect is not so closely related to the amount of rainfall as is the case for the pH-value. The electric conductivity shows low values and small ranges in the summer rainfall affected sites and the widest range and highest values in the drier parts of the winter rainfall area. Besides other salt accumulation affecting parameters such as coastal distance, soil texture etc., here the rainfall regime rather than the rainfall amount seems to have an impact on salt accumulation. Compared to sites with the same amount of rainfall but higher intensities of rain events, drainage of accumulated soluble substance is probably reduced by low intensity rainfalls and less drainage. Additionally, the accumulative effects of ancient termite activity led to patches with higher accumulations in salts. The results of the EC values allow the assumption that in the summer rainfall driven ecosystems drainage occurs regularly, although these might occur only every few decades within the drier regions. The fact that very low EC values are evident in the soils up to a depth of 1 m provides the basis for this hypothesis, which implies drainage over at least 1 m depth. Otherwise, the accumulation of salts, at least chloride from atmospheric deposition, would exceed the found values. These findings are supported by the fact that in the sampled soils often marginal differences in texture go along with differences in EC values, i.e. higher EC values in loamier soils. This also underlines the described drainage effect, which is stronger on sandier soils.

The amount of **organic carbon** in the upper soil layer is very low with 0.1 – 0.4 %. It shows a decreasing trend running from the higher summer rainfall areas in the north to the arid areas in Southern Namibia. With the transition to the winter rainfall area, the content of organic carbon increases again and remains relatively stable with a median of 0.6 – 0.8 % while high ranges indicate a high variety of microhabitat conditions. Two exceptions exist in the overall trend: i) higher contents of organic carbon on the observatories #39 and #40, which are combined with very stable conditions of high pH-values in a calcium carbonate rich environment. This situation obviously favours the persistence and sequestration of organic carbon, also observed in other calcium carbonate rich profiles, and ii) a strong accumulation of organic carbon in a strongly acid nutrient poor environment on the Cape Pensinsula (#33), a situation which hinders the decomposition of organic carbon due to the acid environment.

The sum of **silt & clay** content in soil texture was chosen as an integrative parameter for the content of finer soil particles or sand, respectively. The reason for this decision is that in arid and semiarid ecosystem, finer textured soils are assumed to be edaphically drier sites than sandier profiles subject to the same rainfall conditions. The explanation of this ‘inverse texture hypothesis’ is given as an excursus in chapter 3.2 (observatory #03 Sonop). Median values are predominantly between 5 % (dune sites) and 35 % in almost all of the observatories. One exception is the Knersvlakte (#26, #27) with high values caused by a strong dominance of silt fraction from the underlying phyllite. Except for the dune sites, the overall variability of the texture is relatively high along the transect.

The parameter **rooting space** is used here as an integrative parameter for the availability of fine earth in a given space of 100 % (1 m^3). The graph can be interpreted as a value for the soil physical heterogeneity of the observatories. Again, the dune sites show high values with low variability while the other observatories show very different values ranging from low to high rooting space with various width of the 50 % boxes. In almost all of the cases, at least individual sites characterise wide ranges of the parameters along the transect.

By comparative analyses of soil and vegetation patterns, various impacts of the main ecological drivers along the transect are evident. The overall driving factor in these water-controlled ecosystems is the soil water supply. This again is driven by soil parent material and soil texture, but also partly by osmotic effects of salt accumulations. Nutrients and biotic impacts of termites also play a major role along the transect.

To briefly summarise it can be concluded that in the northern part of the transect, including the woodlands and the thornbush savanna, the texture-driven water supply largely governs the distribution of plant patterns. Occurrence of calcretes further affects this due to soil chemical and physical effects. In particular the observatories #39 and #40 are governed by the properties of calcrete. Besides the direct impact on water supply, the texture also affects the nutrient and pH situation due to different drainage behaviour, i.e. less leaching of finer textured soils. The Thornbush savanna is also strongly affected by the impact of termites, leading to small-scale changes in texture and nutrients, but probably also to a continuous overall rejuvenation of soil parent material. Also in the drier Nama Karoo, effects of texture driven water supply are evident, but these are less visible than in the northern part due to the overall less dense vegetation. With the change in the rainfall regime from summer to winter rainfall in the southern part of the transect, patterns in salt and nutrient accumulation begin to play a more important role. Again, the influence of termites is most evident in several observatories with the occurrence of heuweltjies, fossil termite mounds. These structures cause a strong small-scale variation in soil properties mainly in salinity, calcium carbonate and texture. Additionally, duripans strongly affect the soil physical properties. This influence is highly evident on the observatories #18 and #22 and to a lesser extent also on #20 and #24/#25. Salt accumulations in the Knersvlakte in combination with small-scale changes in pH-values are responsible for a small-scale pattern of different soil chemical properties. In mountainous observatories such as #20, #24 and #25, the influence of the weathering status and the structure of the underlying lithology seems to be a major driver for the small-scale availability of micro-niches, enhancing the local diversity pattern. Within the Cape region, the spatial variability of the overall low nutrient status is not an important factor. In this Fynbos region with higher rainfall, the changes in substrate and underlying lithology are again more significant. This is a minor evidence for the ability to store plant available water than in the northern savanna, but rather due to the degree and length of water logging during the wetter winter months.

Field observations and laboratory data indicate that in most cases the main driving factors for the actual soil situation and its impact on plant distribution are typically the setup of topography, soil parent material, paleosoil, and recent soil development. Thus, it can be concluded that the soil is an integrative driver for biotic components, although the mutual dependency of biotic impact on soils (here predominantly termites) and vice versa should not be overlooked. The impact of recent and ancient termite activity has a strong influence on the soil situation on certain sites, not only due to subtle changes in properties but evident in changes of texture or the development of calcic and duric horizon, which is reflected even in the highest level of taxonomy.

In summary, it can be stated that the variability of soil properties in the studied drylands is high for both, the overall transect and within the observatories. Looking at the different scales of soil patterns along the transect, distinct differences are evident. Whereas the main substrate-driven changes in the northern part of the transect occur at a level of 100 – 300 m, the southern part of the transect is additionally small-scale structured (1 – 100 m). Examples are #22 Soebatsfontein with a high impact of heuweltjie structures and the Knersvlakte (#26 and #27) with small-scale changes in pH-values and salt content. These changes occur within few meters. Additionally, the small-scale changes and structures of bedrock in mountainous and shallow developed sites seem to be a major factor for ecological niches driven by soil physical factors. This ‘flower pot’ principle is very obvious on steep slopes in #21 Numees but also on many other sites on less inclined situations where simply the weathering structure of the bedrock causes a comparable effect. A quantification of this small-scale variety has not been performed to date.

The information regarding soil inventories, soil patterns and the range of ecologically significant interpretations given in the chapters 3 and 4 provide the database for the further development, application and discussion of pedodiversity indices in the chapters 5 to 7. In addition to the development of this reliable database, the results offer valuable ecological information about the study area. Although the focus of this thesis is the interpretation of the soil variability and its quantification, the results provide an excellent basis for further studies regarding soil genesis, landscape development and analyses of processes and mechanisms such as nutrient cycling and carbon dynamics. An ongoing focus within the project is already placed on soil water dynamics and the impact of termites on soil properties in the savanna ecosystem.

5 The concepts of biodiversity and pedodiversity

The notion of diversity is widely used in ecological studies for biotic components (ROSENZWEIG 1995) whereas the idea of diversity applied to abiotic components (often described as geodiversity) is often missing (IBANEZ et al. 1999). Because of the mutual dependency between the biotic and the abiotic environment, the estimation of the ecological value and biodiversity of a given area should incorporate the abiotic component as one major factor causing the pattern and distribution of organisms. Vice versa, present or ancient influences of organisms might be manifested in the abiotic components, e.g. in form of changes in the micro-topography or soil properties.

The lack of concepts for the description and quantification of abiotic diversity is caused by the principal differences in data compared to bioscience. Based on the species concept, it is clearly possible to decide whether a certain species exists in a given area. On the contrary, investigations of the physical and chemical environment lead to data representing a natural continuum. Additionally, the temporal trends of such parameters may range from minutes (temperature) to several thousands of years (texture). However, it shall be noted as well that there exists a wide disagreement regarding conceptualisation and evaluation of biodiversity (RICOTTA 2005).

Despite the ‘continua dilemma’ of soil abiotic parameters, they are predominantly described by classification systems. The application of an index-based system, similar to those used in biological systems, may therefore also be feasible for the abiotic environment. It could provide the opportunity to quantify and compare the complexity of abiotic properties and their relationships to diversity of biotic assemblages. In soil science, this approach has been initialised in the concept of pedodiversity (taken as a variety of pedotaxa, soil horizons and soil properties). This concept represents a useful tool for integrative soil assessment and biodiversity research, as it expresses the major scope of abiotic diversity describing the integrative character of the soil.

This chapter starts with the introduction of the general meaning and ways of quantifying biodiversity as an essential prerequisite for the application of these concepts to pedodiversity. In a subsequent part, the term geodiversity is introduced and defined. Finally, the term pedodiversity is introduced as an integrative parameter of the geodiversity concept, and existing approaches to the methodology and the application of the pedodiversity concept are reviewed.

5.1 Biodiversity: development and meaning

During the last couple of decades, the rather contemporary term biodiversity has undergone an inflationary application in political and scientific contexts. As a result, the term biodiversity expresses various meanings today. Therefore, it seems necessary to make some introductory remarks regarding its development and different definitions prior to applying it in a scientific context.

The term biodiversity is a combination of “bios” which means life (grecian) and “diversitas” which means diversity / differentness (latin). Until the 1980s, the term “diversity” was used to describe the diversity of biocoenoses, while in practice it was mostly restricted to describe only the *species richness* of a community (BEIERKUHNLEIN 1998). However, as the words’ provenance is very much alike, the term “biological diversity” also occurs in earlier literature (MAGURRAN 2004). The first consistent appearance of the term “biological diversity” in literature meaning species richness was in the early 1980s (e.g. LOVEJOY 1980). The fusion of both words to the term *biodiversity* can be traced back to one single event. It was suggested by Walter G. Rosen during the planning of the 1986 “National Forum on BioDiversity” and made popular by WILSON (1988) in his book “Biodiversity” which contains the proceedings of the meeting (HARPER & HAWKSWORTH 1994).

The Convention on Biological Diversity (UNEP 1992) was developed at the `Earth Summit' in Rio de Janeiro in 1992, and interprets biodiversity as the

> *“variability among living organisms from all sources, including inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems”* (UNEP 1992).

By this definition, the term is not restricted to the species level anymore, but is broadened to the genetic as well as the ecosystem level. The latter reflects the increasing perception that biodiversity is not only related to historical factors (e.g. paleo-, phytogeography, paleoclimate, evolution), but also depends to a high degree on the (micro-) climatic conditions and the geodiversity of a given area (diversity of abiotic factors). The broadened definition of biodiversity by UNEP (1992) captures the entire variety and complexity of diversity in species and ecosystems. For this reason, however, one has to be careful with the use of the term biodiversity without specifying the regarded group of organisms, species, communities or ecosystems and the applied methods and scales (SOLBRIG 1994). HARPER and HAWKSWORTH (1994) propose the adjectives “genetic”, “organismal” and “ecological” to specify the three levels of the UN definition.

Recently, HUBBELL (2001) returned to a more focused definition. He defines biodiversity to be *“synonymous with species richness and species abundance in space and time”*. As the use of the term biodiversity today ranges from natural science over politics to social sciences and implicates very different meanings depending on the context (e.g. extinction of species, resource assessment of potential medicinal plants), the definition of HUBBELL (2001) leads back to the origin of diversity studies in natural sciences, i.e. the variety and abundance of species of a defined study unit. RICOTTA (2005.) reviewed selected aspects of the meaning and differences of the terms biodiversity, diversity, and diversity index and gives valuable insight into the overall discussion of the concept of biodiversity measures. In an overview, HAMILTON (2005) discussed the relationship of species diversity and biodiversity.

Apparently, the terms “biodiversity” and “biological diversity” are used interchangeably by many authors (MAGURRAN 2004). In an etymologic way, the term “biotic diversity” is more precise than the term “biological diversity”, as biotic diversity defines the properties of the biotic components and not the diversity of the different biological disciplines.

5.2 Biodiversity: The principles of measurement

The measurement of diversity, also called diversity statistics, offers numerous techniques to describe the variety of a regarded assemblage or area. The theory behind measurements can be reduced to a few assumptions. Following HUSTON (1994), the concept of diversity exists of two primary components and two value judgements. The primary components are statistical properties, which are common for any mixture of objects and give information about i) the number of different object types and ii) the number of individuals within each object type. The value judgements are i) if the selected classes are different enough to be considered as separate type of objects and ii) if the individuals in a particular class are similar enough to be considered as the same type.

This rather simple definition of the diversity measure components of shows clearly how taxonomy and other distinctions or groupings of objects influence the results in the quantification of diversity. A further important issue in this context is that the measurement of biodiversity always has a comparative background. As a single value is not informative, measurements mainly focus on whether one domain is more diverse than another, or whether diversity of a monitored site or community has changed over time due to processes such as succession or degradation (MAGURRAN 2004). One must always define the questions to be answered very clearly and likewise the quality and quantity of the data used for diversity analyses. This should include an explicit description of the sampling methodology and the relationship of the sampling amount and the size of the study area or assemblages respectively. To reduce errors, it is strongly recommended to apply the same methodology in comparative diversity studies (MAGURRAN 2004).

The concept of biodiversity applied most frequently deals with taxic measures. Taxic measures can be used at the species level or at the level of groups of higher taxa like phyla, orders, families or other grouping concepts. Further concepts are molecular measures or phylogenetic measures.

In the context of species diversity, which is the most frequently used level of application, there are two main components to distinguish: i) the variety of species which can be regarded as species richness and ii) the distribution of individuals among these species which is termed evenness or equitability. Information about these components in a given community provides the basis for the generation of a more abstract description of diversity. The methodologies which deal with the measuring of diversity can be grouped into following classes, which are subsequently explained in separate (after MAGURRAN 2004):

1. Indices of richness: Number of objects (taxa) within a sampling unit (area, community).
2. Indices of evenness: These indices refer to the distribution of abundance within the number of objects.
3. Object abundance models: These models describe the abundance of objects within a sampling unit (e.g. number of individuals per taxa). The diversity of a sample is described by a model, which provides the closest fit to the abundance.
4. Diversity indices which combine the richness and evenness components
5. Species accumulation curves which cumulate the number of species along a sampling sequence
6. Differentiation diversity which enables comparison of different assemblages

Although not all of these aspects of diversity measures are applied in the pedodiversity analyses of this study, they are explained briefly in the following sections in order to provide the reader with a comprehensive background on the commonly applied methods and concepts. Further explanations are given in MAGURRAN (2004) and RICOTTA (2007).

Indices of Richness

Species richness seems to be a simple measure of diversity. Species richness can be defined as the number of species '*S*' of an assemblage, however, it has to be clear which taxonomic level is regarded (e.g. biological species, phylogenetic species etc.). Often the species are unknown and one has to deal with morphotypes for diversity measures.

Problems may arise when a population is to be described in its species richness while the data basis only consists of random samples. In this case, species abundance may alter the number of required samples for a "real" capture of species richness. In an evenly distributed population fewer samples are needed to capture the entire species range than in an unevenly distributed population. This has to be taken into account when comparing species richness of different areas, irrespective of the identical applied methodology and number of random samples.

If the study area is delimited in space, the sampling restricted to a certain time window and the entire population captured by the study, the estimation of richness is very valuable and reliable. If only samples can be obtained, which is regularly the case, it is helpful to split information into a "numerical richness" (ratio between number of identified species and sampled individuals) and a "species density" (total number of species) (KEMPTON 1979).

Two of the best-known richness indices are the Margalefs index D_{Mg}

$$D_{Mg} = \frac{(S-1)}{\ln N}$$

and the Menhinick's index D_{Mn}

$$D_{Mn} = \frac{S}{\sqrt{N}}$$

where *S* is the number of species and *N* the total number of individuals. In comparison to a total number of species, these indices attempt to correct for sampling size by including the number of individuals. However, both measures remain strongly influenced by sampling effort (MAGURRAN 2004).

As diversity in the ecological sciences is not only defined according to the number of species, but also according to their abundance or evenness, one has to be careful with the interpretation of high species densities in the term of diversity. The presence of rare species can inflate the species number and hence gives a poor description of diversity in its ecological meaning.

Indices of Evenness

The term evenness describes the distribution of abundance within the number of objects (species) within an investigated area or sample. Evenness is often used in combination with richness indices for integrative diversity analyses (see diversity indices below). The underlying concept for such combined indices is that a high evenness value (maximum equality of the object abundance) has to be incorporated positively and therefore raises the overall diversity value.

The single measurement of evenness (E) is mostly obtained by calculating the relationship between the observed values of a diversity index *H'* and its maximum value for the regarded sample (PIELOU 1969):

$$E = \frac{H'}{H\max} = \frac{H'}{\ln S}$$

where *H'* is the Shannon diversity index (see diversity indices) and *S* is the richness in number of species. *E* takes values between 0 (highly non-uniform distribution of abundance) and 1 (all object abundances are evenly distributed). Often the abbreviation *J'*or Pielous index is used for this measure. For the interpretation of this evenness index one should know that up to a number of approximately 25 species this index is still dependent on species richness (SMITH & WILSON 1996).

Another common evenness measure is derived from the Simpson diversity index D (see diversity indices below):

$$E_{1/D} = \frac{1/D}{S}$$

where *D* is the Simpson diversity index and *S* is the richness in number of species. The measure ranges from 0 to1 and it is not sensitive to species richness (MAGURRAN 2004).

These two examples shall represent the wide range of evenness measures, each with different strengths and weaknesses. MAGURRAN (2004) provides an overview and an explanation of the most frequently used and new, recently developed indices. As it can be difficult to decide which evenness index is best to apply for which context, SMITH and WILSON (1996) conducted an evaluation of available measures. They formulate requirements for evenness measures and give an overview of the capability of the different indices to capture a set of desirable features. MAGURRAN (2004) concludes that to date the Simpson's evenness index probably provides the best performance. It is widely used and therefore a recommended measure of evenness that is independent from species richness. According to SMITH and WILSON (1996), this independency is the most important requirement for the quality of evenness measures.

Diversity indices

The measurement of biodiversity is mostly quantified based on combined diversity indices which express a degree of heterogeneity including richness and evenness. According to MAGURRAN (2004) the indices can be roughly grouped into "parametric" and "non-parametric" indices. The first group uses a parameter of the species abundance model whereas the latter makes less or different use of the underlying species abundance distribution. Here, the focus is on the so called "non-parametric" measures. An example for the parametric measures is provided in the description of the species abundance models (see below).

The development of indices for the numerical description of diversity and its properties began with the work of SIMPSON (1949) and SHANNON & WEAVER (1949). Originally, the concept is derived from the theory of information, which deals with the question of uncertainty in information content. The uncertainty is increasing with an increasing number of objects (here species) and an increasing equal distribution of individuals among these objects. The uncertainty, also called the Shannon-Entropy (a measure of the loss of information in a transmitted signal or message), is regarded as a measure of diversity (SHANNON & WEAVER 1949, PIELOU 1975, MAGURRAN 2004). The reason for the adaptation of this combination index in the field of ecology is in the assumption that climax situations inhabit the highest species richness and the highest evenness of a system (CHAPIN et al. 2000).

Indices of diversity therefore often incorporate both, species richness and species abundance in one single figure. Higher species numbers and higher evenness values increase the degree of diversity. However, due to the range of different indices, which tend to strengthen either richness or evenness, the strength and weakness of these indices have to be taken into account in order to interpret them correctly. This is important, as in certain situations the use of different diversity indices can lead to opposite trends in the results (HURLBERT 1971, NAGENDRA 2002). Information on the strength and weakness of different diversity indices are given in MAGURRAN (1988, 2004). Here, the most frequently used indices with different performances are introduced.

One of the most frequently applied diversity measure is the **Shannon index.** It was originally developed by Shannon and Wiener and mistakenly often referred to as the Shannon-Weaver index, as the original formula was published by SHANNON and WEAVER (1949) (MAGURRAN 2004). The assumption behind this index is an infinite community that is randomly sampled while all species are represented in the sample. Its mathematical expression is as follows:

$$H' = \sum_{i=1}^{S} p_i \;\; x \;\; \ln p_i$$

where *H'* is the negative entropy (negentropy) or diversity of the community and is the proportional abundance of the i^{th} species. In the case of calculating with samples and not with the entire community, the true value of p_i is unknown and is estimated by n_i / *N* (proportional abundance of the i^{th} species to the total number of individuals in the sample).

The value of the Shannon index derived from empirical data usually ranges from 1.5 to 3.5 and rarely surpasses 4 (MAGURRAN 2004). Interpreting results within this narrow range is difficult, as the value cannot be used as concrete information. Although the Shannon index stresses the richness component and rare species, increases or decreases in *H'* can also be a result of changes in the abundance pattern while the species richness stays the same. Additional calculations of single richness or evenness indices of the compared assemblages can solve the problem of inaccurately interpreting the combined diversity indices.

The advantage of all diversity indices is that they include both important components of diversity within one index, i.e. species richness and abundance (evenness). However, at the same time it is not detectable whether an increase in the index occurs because of greater richness, or greater evenness, or both (MAGURRAN 2004). BUZAS and HAYEK (1996) and HAYEK and BUZAS (1997) provide a solution for this problem inherent to the Shannon index. Following HEIP (1974) they use a modified measure of evenness which is less sensitive to species richness (E_{Heip} = $e^{H/S}$) and then calculate the sum of the natural log of this value ($ln(E_{Heip})$) and the natural log of species richness (*ln(S)*) which is equivalent to Shannon Index *H'*. By this, the formula can be splitted into two parts, which allows a separate interpretation of changes in richness and evenness.

$$H' = \ln S + \ln E_{Heip}$$

Another diversity index, but less commonly used, is the **Brillouin Index.** Its application is recommended when the randomness of the sample cannot be guaranteed. It is calculated as follows:

$$HB = \frac{\ln N! - \sum \ln n_i!}{N}$$

Compared to the Shannon index, the Brillouin often gives correlated diversity estimates. However, applied to the same data set, the Brillioun index will always show lower values. This is because the Brillouin regards the data set as complete without any uncertainty about unsampled individuals or species, which is included in the estimation of the Shannon index. Another distinguishing feature in comparison to the Shannon index is that the Brillouin index is sensitive to the number of individuals in the case of an even species distribution. While the Shannon index results in the same diversity for two samples having the same abundance relationship, the Brillouin gives slightly higher values for the community with the higher number of individuals (MAGURRAN 2004).

The Shannon and the Brillouin indices described above emphasise the richness component of diversity. Another group of diversity indices places greater emphasis on the abundance pattern of the most common species. These indices are often referred to as dominance or evenness orientated measures. A widely used diversity index stressing the evenness component is the **Simpson index** (SIMPSON 1949), which is calculated as follows:

$$D = \sum_{i=1}^{S} p_i \;\; x \;\; p_i$$

where p_i = the proportional abundance of the i^{th} species and D gives a measure of diversity. As in the original form diversity decreases with increasing D-values, the Simpson index is often expressed in a reciprocal form as 1/D or 1-D, which expresses increasing diversity with increasing values. The Simpson index defines the probability of any two randomly selected individuals belonging to different species.

According to BACK and TÜRKAY (2002), the corrected form when dealing with a finite community is:

$$D = \sum_{i=1}^{S} \left(\frac{n_i [n_i - 1]}{N [N - 1]} \right)$$

where n_i = the number of individuals of the i^{th} species and N = the total number of individuals.

According to MAGURRAN (2004), the Simpson's index is one of the most meaningful and robust diversity measures available. However, one has to be careful with interpreting this index as an evenness-dominated measure when the species numbers are low. MAY (1975) has shown that only when the species number exceeds 10, the abundance distribution becomes more important in determining the index.

The **Berger Parker index**, d, is a simple index, which gives information about the proportional abundance of the most abundant species within a sample. It is therefore only a dominance measure, which is calculated by

$$d = N_{max} / N$$

where N_{max} is the number of individuals in the dominant (most abundant) species class. The resulting values range from nearly 0 to 1 (entire sample consists of one species). Used as a diversity measure, the reciprocal form 1/d is recommended, as diversity increases with increasing values. MAY (1975) concludes that it is the most satisfactory diversity measures available.

Abundance models

One of the earliest observations made by plant ecologists is that species are not equally common in a given community. Graphical ways to describe these patterns of occurrence are the species abundance models. These models emphasise abundance by utilising species richness information and thus provide the most complete mathematical description of a given data set. Species abundance models are generated by means of graphing the abundance of each species against its rank order abundance from the highest to the lowest. The data is described by the model which provides the closest fit (Log normal distribution, Geometric series, Logarithmic series, Broken stick model). Abundance models are useful for a rapid assessment of assemblages or for the monitoring of succession or environmental impacts. For instance, steep plots signify high dominance whereas shallower slopes imply a higher evenness component in the data set. A detailed description of the models and their application to empirical data is given in MAGURRAN (2004).

A good example is the frequently applied approach of Q-statistics, which uses the interquartile slope of a cumulative species abundance curve to measure diversity. The restriction to the interquartile region provides a stable measure, as neither very abundant, nor very rare species influence the result. Its equation is:

$$Q = \frac{\frac{1}{2} n_{R1} + \sum_{R1+1}^{R2-1} n_r + \frac{1}{2} n_{R2}}{\ln(R2 / R1)}$$

with n_r = the total number of species within the quartiles, *R1* and *R2* = the 25 % and 75 % quartiles, n_{R1} and n_{R2} the number of species in the class of *R1*, or *R2* respectively .

Species accumulation or species area curves

Species accumulation or species area curves are a common method used in ecology to determine the species richness and its spatial behaviour of an area by taking a series of samples (e.g. quadrates, traps etc.) (ROSENZWEIG 1995, SOUTHWOOD & HENDERSON 2000). The rate at which new species are added to the accumulative curve of species as a function of the number of samples allows important repercussions about the species richness and the species abundance of the whole assemblage. Sample series along a transect or a continuously increasing sampling area (such as Whittaker Plots, see Wilson & SHMIDA 1984) provide useful information on habitat borders, patch sizes and regional trends of species distribution. Estimating species richness for the entire assemblage from individual samples can be obtained by extrapolation of species area curves or by the use of species abundance models.

Differentiation diversity

Any investigation of ecological diversity requires the definition and limitation of a studied area. Depending on the ecological entity or the investigated geographical area, different types of diversity can be distinguished. The most common concept is the "**inventory diversity**" of WHITTAKER (1972, 1977). Whittaker distinguishes four levels of diversity. On the smallest scale he defines "**point scaling diversity**" which represents the diversity of a micro-habitat sample taken from a homogenous habitat. The diversity of this homogenous habitat as a whole builds the second level of differentiation termed "**alpha-diversity**". The third level of inventory diversity is the "**gamma-diversity**", which is defined as the diversity of a larger unit such as a landscape and comprises several areas of alpha diversity. The fourth level, the "**epsilon-diversity**" characterises the diversity of a region, which includes a group of gamma-diversities. Whereas the epsilon-diversity can be regarded as a measure for larger biogeographic areas, the point scaling diversity can already be applied on a single square metre. However, the inventory concept is not limited to defined areas; it can be easily adapted to other purposes with different scales to describe the diversity patterns of an area or a community at different levels. In most ecological studies, alpha diversity is used as the lowest level for describing "within habitat diversity" (MACARTHUR 1967).

In order too analyse trends along gradients (e.g. species turnover) or to describe changes in time series such as succession processes, differentiation measures are required. Whittaker defines three levels of differentiation diversity to match his four diversity scales (pattern differentiation diversity, beta differentiation diversity and delta differentiation diversity). The first stands for the differentiation between samples from the same homogenous habitat, whereas the delta diversity is a parameter for the quantification of a number of gamma diversities. The **beta diversity** is the most commonly used term to compare the diversity between different habitats and is essentially the same as the term "between habitat diversity" created by MACARTHUR (1967). WHITTAKER (1972) originally defined beta diversity as a measure of change in diversity between samples along a transect or environmental gradients, but the concept can also be applied to different spatial configurations.

The application of the beta diversity concept (in a broader sense) can be grouped into three classes:

1. measures to examine the difference between two or more areas in the alpha diversity in relation to the gamma diversity.
2. measures of differences in species composition between areas of alpha diversity (similarity /dissimilarity measures) which requires species identities.
3. measures of turnover with species area relationships

Within a wide range of beta measures related to class 1, MAGURRAN (2004) recommends the following two: The oldest and one of the simplest measures of beta diversity was developed by WHITTAKER (1960):

$$\beta_W = S / \overline{\alpha}$$

where S = the total number of species recorded (γ diversity) and $\overline{\alpha}$ = the average sample diversity measured as species numbers. Values of two compared samples may range from 1 (complete similarity) to 2 (total different species composition). A more appropriate scale is achieved by subtracting 1 from the result and the range starts with 0. The maximum possible value equals the number of samples included in the mean calculation of α.

Another measure of beta diversity is an index proposed by WILSON and SHMIDA (1984). The index is calculated by using information about the gain and loss of species:

$$\beta_T = \frac{[g(H) + l(H)]}{2\overline{S}_j}$$

where $g(H)$ = the number of species gained and $l(H)$ = the number of species lost and Sj = the average sample diversity measured as species richness.

Indices of similarity or dissimilarity (class 2 above), which measure differences in species composition between areas of alpha diversity, represent another possibility for the description of beta diversity. However, these concepts require established species identities, because they identify the presence or absence of a single species in the compared units. When comparing two sites, *a* is the number of species found in both sites while *b* and *c* are the number of species found at only one of the sites. Two simple coefficients are:

JACCARD (1908)

$$C_j = \frac{a}{a+b+c}$$

and SÖRENSEN (1948)

$$C_S = \frac{2a}{2a+b+c}$$

The simplicity may also pose a disadvantage as the coefficients ignore the *relative* abundance of the species. To overcome this weakness, similarity indices have been developed which are based on quantitative data, e.g. the Sörensen quantitative index (MAGURRAN 1988):

$$C_N = \frac{2\,jN}{(N_a + N_b)}$$

Where *Na* = total number of individuals on site A, *Nb* = total number of Individuals on site B and *2jN* = the sum of the lower of the two abundances for species found on both sites.

The measure of species turnover with species area relationships (class 3 above) uses the slope within a species area plot. The slope z in the relationship between log(S) and log(A) or the slope m in the relationship between S and log (A) can be used as a measure of turnover in species composition (MAGURRAN 2004).

Each measure of beta diversity or of the differentiation diversity should be clearly defined in terms of scale and applied methodology. Different sizes of sample areas in the same landscape can lead to different results and consequently differences in interpretations of the system.

Concluding remarks on diversity indices

Although not all of the introduced methods and indices are applied in this study of pedodiversity analyses, the introduction is necessary for the understanding of the biodiversity concept applied in biology, primarily based on the ongoing debate about the validity of measures (RICOTTA 2005.). Uncertainties in this field led to comments like the 'non concept of species diversity' (HURLBERT 1971) or POOLE (1974) who questioned whether diversity measures are 'answers to which questions have not yet been found'. Thus, there is ongoing development regarding alternative techniques of diversity measures (e.g. ROUSSEAU et al. 1999).

It shall be raised again that the original concept is borrowed from information mathematics, i.e. it is not restricted to biological science. Furthermore, the background of classification concepts in biology is very important to consider. In general, when diversity indices are applied and different sites are compared, one should always bear in mind that the varying species concepts in different groups of organisms, or even within a single group, are a major cause of uncertainty to all aspects of biodiversity (HARPER & HAWKSWORTH 1994; GASTON 1996). Regarding a species as a standard unit cannot lead to an interpretation of its taxonomic distinctness or taxonomic distance to other species. In terms of assessing and conserving biodiversity, the taxonomic diversity might be an important aspect, as communities may be identical in terms of richness and evenness but differ in the taxonomic diversity of their species.

The aspect of taxonomic distance has been implemented in indices, which use the path length through the phylogeny of an assemblage (e.g. Rao's entropy *Q*, for details see MAGURRAN 2004, FAITH 2002). As discussed in the following chapter, the problem of the taxonomic distinctness also arises in the measurement of soil diversity when using existing classification concepts. Another shortcoming of the diversity indices is that a differentiation between "ecological important species" (keystone species) and less important species is not possible. This can be summarised under the term 'functional diversity' (MASON et al. 2005, PETCHEY & GASTON 2002) which is much more difficult to obtain. One further approach is to separate into functional groups or traits (RICOTTA 2003*s.o.*).

In summary, the diversity index concept follows the hypotheses that all species are equal (also in their distinctness) and that the highest diversity in terms of richness and evenness stands for the stability and productivity of an assemblage (diversity-productivity and diversity-stability debate, see MCCANN (2000), TILMAN et al. (1997)).

5.3 Geodiversity: Development, meaning and use

When looking at the field of geodiversity, first of all the question "why should we study the diversity of the abiotic environment?" needs to be answered. While the measurement of biodiversity has a long history in ecology and recently gained an important meaning in terms of conserving and preserving the world's species richness, the diversity of the abiotic environment has not so far attracted equal attention. Due to this void, many patterns and processes of biodiversity and their relation to the ecosystems cannot be understood. Quantitative measures in terms of abiotic diversity could, however, offer valuable potential for the analyses and quantification of various causalities.

The assessment of abiotic diversity is crucial for e.g. the interpretation of the geological history of the earth, past and present climates and landscapes, and the origin and evolution of life. It is an essential component in the understanding of patterns and processes in landscapes and their biotic entity. Despite the awareness of problems such as species extinction and environmental changes in the field of biology, earth scientists have only recently become involved in environmental conservation strategies of the abiotic components (GRAY 2004).

The term geodiversity is mostly used when the entire abiotic diversity is described. However, as the notion of diversity as a qualitative and quantitative concept has just recently emerged in earth sciences, only few quantification approaches exist. Due to this initial status, somewhat unclear definitions and uses of terms representing abiotic diversity are in use. In addition, their hierarchical structure is rather chaotic. Therefore, this chapter introduces firstly the basic concept of geodiversity. In a second section follows a review regarding the current status of the concept of pedodiversity.

The notion of special geological or geomorphological features of the abiotic environment has a long history, assumingly as long as the notion of diversity in the biotic environment. Already during the nineteenth century, geological nature reserves were established in Europe and in the USA. Today, many countries have areas or sites that are protected at least partially for their geological or landscape interests (GRAY 2004). However, often this geoconservation only focuses on geological or geomorphological features and even this reduced approach is weakly developed in most countries and lags behind biological conservation, or forms only a very small part of local nature conservation approaches. Meanwhile the importance of geological heritage conservation is recognised by international institutions such as the UNESCO World Heritage list of conservation. Recently the 160,000 ha Richtersveld Cultural and Botanical Landscape of dramatic mountainous desert in the northwestern part of South Africa became part of this list. Regardless of these geoconservation aspects, the term geodiversity is rarely used in applied contexts.

Earth scientists began to use the term geodiversity to describe the variety within the abiotic nature from the 1990s onwards (e.g. GRAY 2004, BARTHLOTT et al. 1996, BRILHA 2002, STANLEY 2000, TWAITES 2000, JEDICKE 2000, 2001, KOZLOWSKI 2004). Contrary to the former landscape conservation approaches, geodiversity as a concept is not focused on special geological or geomorphological features of the landscape; it is describing the diversity of the whole range of the abiotic environment in its spatial dimension. Geodiversity focuses on the entity of abiotic environment as a quality by itself and follows the assumption that it is probably the most important parameter influencing biodiversity on a regional to habitat scale. This strengthens the perception that any investigation of the biotic environment should consider the abiotic environment as both systems have coevolved over long time periods and are mutually dependent (PHILLIPS 1999).

The concept of geodiversity is still in an initial phase and to date definitions are applied to different contexts and meanings. The term geodiversity is not "officially" defined as is the term biodiversity in the United Nations convention (UNEP 1992). GRAY (2004) reviewed a number of definitions, which were mostly developed with respect to particular topics or countries. Aiming at a more conceptual frame of the term he defines:

> *"Geodiversity: the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (land form, processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems"*.

Whereas Gray does not explicitly include climate and hydrology, BARTHLOTT et al. (1996) define geodiversity in a broader sense as the sum of abiotic factors ranging from climatology, geomorphology, topography, geology, pedology to hydrology. LESER and NAGEL (1998) define geodiversity as the diversity of non-biotic systems; the structure, function and dynamics of the abiotic part of the ecosystems such as the geosphere, climosphere and hydrosphere. Common to all definitions is that the term is not restricted to a spatial scale. Geodiversity theoretical applies to various scales ranging from the global scale of continents and oceans to elemental scales of atoms and ions. The most common application is the habitat to regional scale. In order to make its meaning more precise, the term should always be complemented with information about the applied scales.

The combination of geo- and biodiversity can be regarded as main component of the landscape diversity (LESER & NAGEL 2001). This includes not only the current status of an ecosystem but also the processes, dependencies, interactions and mutual influences between geo- and biodiversity and land-use systems. Landscape diversity is therefore more than the sum of its parts. It reflects the structural, functional, spatial and temporal patterns inherent to landscape ecosystems (SCHULZE & GERSTBERGER 1993).

The term "ecological diversity" has frequently been used in the context of biological diversity, however, the attribute ecological was rather used in the sense of biotic community description and not as a term that includes the abiotic components, too. PIELOU (1975), for example, defined it as "the richness and variety (…) of natural ecological communities". MAGURRAN (1988) also used this term as the title for the former version of "Measuring biological diversity" (MAGURRAN 2004). At present, ecological diversity is used synonymously with biological diversity in its broadest definition (UNEP 1992) which also includes the diversity of ecosystems.

BARTHLOTT et al. (1996, 1999) suggested using the shortened term "ecodiversity", meaning the total diversity of a region, i.e. a combination of geo- and biodiversity. They suggest the use of this term as an alternative to the term landscape diversity as the latter is used for evaluating gamma-diversity according to WHITTAKER (1972). On the other hand, LESER & NAGEL (2001) mentioned that Whittaker did not use the term landscape diversity and that WHITTAKER's (1972) gamma diversity is "richness in species in a range of habitats" (e.g. a landscape) and therefore does not include the abiotic or land-use part of the landscape. LESER & NAGEL (2001) defined ecodiversity as a generic term containing many individual diversities, but cannot include human activities like the term landscape diversity. Therefore, LESER & NAGEL (2001) recommended the further use of "landscape diversity" in their above mentioned definition which should not be confused with the "richness in landscapes" of a specific area.

Landscape diversity with meaning of richness is employed by landscape ecologist to describe the composition of a landscape using single numbers. The applied methods are calculating indices by the use of established diversity measures like the Shannon or the Simpson index. The principle is to regard specific land types as species and their coverage as abundance (e.g. NAGENDRA 2002). Further approaches include measures of spatial configuration such as connectivity, adjacency and fractal geometry. An overview of quantification techniques is given in GUSTAFSON (1998)

Despite of the more theoretical discussions and findings on definitions and hierarchical concepts of abiotic diversity and the pattern orientated landscape ecology, there exist only few concepts about the qualitative and quantitative measurement of geodiversity. Although there is a wide range of descriptive tools available, a quantitative tool box similar to diversity measures in biotic sciences is not established or just for specific cases. One index for the quantification of geodiversity has been developed by BARTHLOTT et al. (2000). Using a geographical information system, they created a geodiversity map of the South American continent which shows similar trends in comparison to the biodiversity patterns. They used available data on topography, climate, and soil. However, as data on soil and climate are similar units across large areas the topography influence the index strongest. Besides this rare example of integrative measure of several abiotic factors, the topodiversity is often used as a simplified heterogeneity measure (e.g. THUILLER et al. 2006).

Often the term geodiversity is used even without definition and information on scale as a mere expression of environmental heterogeneity. In Figure 204 a simple scheme clarifies the hierarchical levels of the different terms introduced above and gives an orientation of the use of geodiversity in this study.

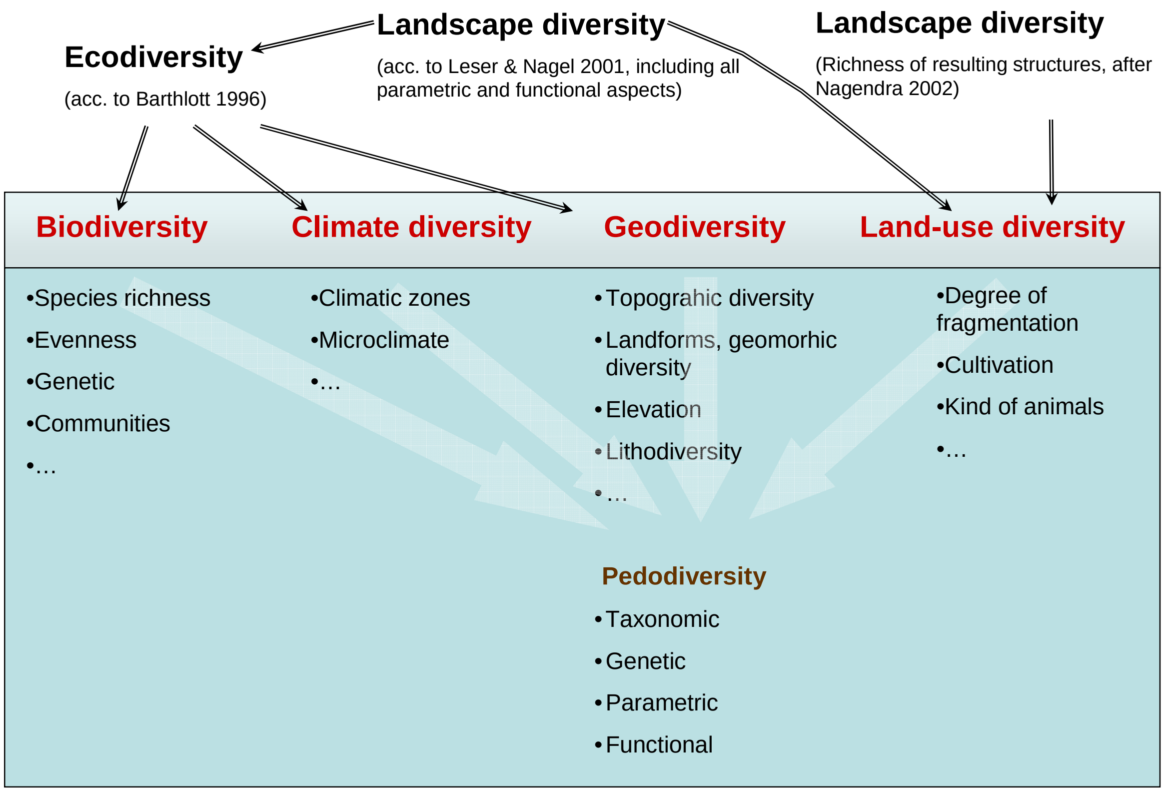


Figure 204 Hierarchical structure scheme of the different diversity concepts

5.4 Pedodiversity: Development, meaning and application

Spatial variability of soils has long been recognised as a crucial issue for the understanding of ecological patterns. Main reason for the high value of soil information is that within the range of abiotic environmental factors, soils are the best single predictor of habitat heterogeneity, because they reflect the influence of many environmental factors (IBANEZ 2005). This includes actual dynamics as well as historic aspects. Figure 204 illustrates this hypothesis.

Similar to geodiversity, no precise definition exists and the term pedodiversity is used in numerous contexts when describing soil variations. Following various recent publications, in this study, pedodiversity is regarded as a concept equivalent to biodiversity. This also implicates the use of diversity measures established in ecology. Because the soil is a continuum, taxonomic or parametric concepts are required to segregate it into taxa or classes (soil continuum dilemma, see IBANEZ & BOIXADERA 2002, YAALON 2003). Thus, before describing the concept of pedodiversity in detail and reviewing the existing literature on this topic, a brief introduction to the main principles to describe and classify soils or soil properties is provided.

5.4.1 Description and classification of soil heterogeneity

In soil science, different systems and techniques to qualify, quantify and regionalise the continuum of soil properties exist. They can be grouped into three principal approaches: i) soil classification by a taxonomic system ii) soil regionalisation, which emphasises the spatial component and its description on the basis of classification, and iii) geostatistics or pedometrics, which attempt to regionalise and describe the spatial structure of soil properties.

The earliest system, soil classification, partitions the soil continuum into rather discrete classes of similar (range) properties (for a historical overview see BOCKHEIM et al. 2005). Such a classification system can either have a scientific purpose in terms of pedogenesis or uses soil properties for more applied purposes such as land-use. Often a combination is applied, which results in a rough differentiation of the main soil features. To increase the degree of information, most classification systems raise the accuracy of the description by breaking the discrete units further down to different levels (e.g. FAO world soil map legend, WRB (FAO 1998 & 2006) or US Soil Taxonomy as international applications; numerous national systems; for an overview see ESWARAN et al. 2003).

Classification is only a tool for the descriptions of difference and aggregation in a taxonomic sense. The description and aggregation in a spatial context (e.g. soil maps) is a task, which uses classification to name the elements, but also requires an aggregation concept for the spatial dimension. To structure the hierarchy and to give a spatial dimension to the term soil, the concepts of the pedon and the polypedon where introduced by JOHNSON (1963). Based on the work of NEEF (1963) to structure the dimension of landscapes, HAASE (e.g. 1970, 1989) and Schmidt extended the structural concept of pedon and polypedon to higher aggregation levels of defined dimensions in the landscape and adapted it for mapping purposes. Additionally, they defined the degree of the soil description within the different hierarchical levels of aggregation. This was an important step in the regionalisation of the soil structure, as it was the first concept for a spatial description of soil with a taxonomic approach. The development and the description of the hierarchical concept is summarised in SCHMIDT (1997). Here, only a brief introduction to the concept is given.

The pedon is the smallest unit of the soil body used in soil mapping. One has to distinguish between a soil profile, which allows a two-dimensional view of the soil, and a pedon, which is a three-dimensional body with a certain surface area, which might range from 1 to 10 m^2. A pedon always contains a certain heterogeneity which is due to the nested structures of atoms, minerals and microhabitats (MIEHLICH 1976), the vertical differentiation of properties and dynamic properties variable with time (e.g. temperature, water content, pH-value).

A group of neighbouring pedons with "similar" properties are called polypedon. Within a polypedon there exists a variance of soil properties, which may occur in different scales and with different variation coefficients. Within a polypedon, all soils belong to the same systematic unit (e.g. a soil series in USDA Soil Taxonomy). A polypedon is a real physical soil body, which is limited by "not soil" or by pedons of unlike character in respect to criteria used to define the lowest hierarchical unit (JOHNSON 1963).

SCHMIDT (1997) therefore defines a polypedon as an aggregation, which is only characterised by systematic categories and might show irregular borderlines or the inclusion of other polypedons. As this definition is not useful for a spatial characterisation, Haase and Schmidt introduced the term pedotop which builds a homogenous area in the sense of the topic dimension after NEEF (1963). A pedotop is not homogenous in its taxonomic soil properties; but stands for one polypedon containing pedons of other polypedons or transition zones. It is therefore an "imprecise" polypedon, which is defined by its dominant taxonomic unit while it also incorporates a certain variability and transitions frequently. HAASE and SCHMIDT (1970) assign four levels of differentiation for the pedotop that allow an interpretation of the degree of heterogeneity. A pedotop is the smallest unit for soil mapping in the topic dimension. Due to the finely scaled changes, which are not possible to map in detail, a combination of different polypeda or pedotops is often summarised as a pedo-complex. A group of pedotops or pedo-complexes is called soilscape or pedochore, characterised by a certain soil association. Soilscapes can be aggregated to soil provinces (pedomacro-chore) which are again grouped into soil regions. The highest hierarchical level is the soil-zone mainly influenced by climatic factors. In summary, the principle of the nested aggregation with the definition of the dimensions is a precondition to analyse and compare soil spatial distribution with a reproducible and comparable technique.

Another approach, particularly used for the spatial description of soil properties and commonly named geostatistics, regards the soil as a suite of continuous variables and seeks to describe the way soil properties vary over a certain area. Geostatistics applies statistical tools and models for the processing of spatial observations and focuses on the spatial description and prediction of soil properties (for an overview see GOOVAERTS 1999, HEUVELINK & WEBSTER 2001, WEBSTER & OLIVER 1990, 2001, PHILLIPS 2001, MULLA & MCBRATNEY 2000). Since the early 1990s, a group of soil scientists who mainly use geostatistics established the term “pedometrics” to discuss soil-relateted geostatistical approaches. Meanwhile the official term is “International Working Group on Pedometrics – Commission 1.5 in Division 1 of the International Union of Soil Sciences (IUSS)” (www.pedometrics.org). Pedometrics is now defined as

> “*the application of mathematical and statistical methods for the study of the distribution and genesis of soils*”.

5.4.2 Literature review on pedodiversity

The basic idea behind pedodiversity is not a new one. Any investigation of soil patterns within a certain area results, at least in the mind of the researcher, in a perception of the richness in soils and pedological diversity. Dokuchaev already paid special attention to the great diversity of soils, convincingly explained as related to the “infinite diversity of natural conditions.” (DOBROVOL’SKII 2007). However, the first explicit and conceptual mention of pedodiversity is much more recent. The Russian school of soil geography (FRIDLAND 1976) was the first to mention the importance of this concept in its studies of soilscape pattern. HOLE & CAMPBELL (1985) extended the concept by concrete proposals for indices describing diversity in soilscapes. SCHMIDT (1978) suggested indices for the description of heterogeneity, which are based on the number of pedotops within a certain area. He included the spatial structure by the relationship of the total length of borderlines and the number of intersections. However, despite the quality of these earlier approaches, their application has not been widely used.

Since the early 1990s the term pedodiversity appears in literature more frequently in the context of the development of a suitable framework for pedodiversity measures based on existing ecological measures. Most of the task to employ diversity measures in the context of the abiotic environment has been done by J.J. Ibanez and co-workers. IBANEZ et al. (1990) used diversity indices to describe the complexity of pedogeomorphological landscapes in a study of the hierarchical organisation of drainage basins in Spain. He also applied this methodology to analyse the evolution of this system (IBANEZ et al. 1994). MCBRATNEY (1992) addressed the application of the pedodiversity concept in pedological research and gave an example of the estimation of taxonomic pedodiversity on a regional scale. IBANEZ et al. (1995) reviewed the concepts and definitions of diversity and explored the possible application of biological diversity models and indices to soil databases on different scales. They found that the patterns of biodiversity, geomorphological diversity and pedodiversity have great similarities according to “species”-area relationships and abundance models described in ecological literature. This suggests that there are universal regularities which are common to the organisation of biotic and abiotic structures. IBANEZ et al. (1995) therefore raised the need to draw testable hypotheses for the explanation and the quantification of the underlying causalities. In a further approach, IBANEZ et al. (1998) analysed the diversity of the world’s pedosphere by using the major soil groups of the FAO world soil map. They used evenness (Pielou) and diversity (Shannon) indices to describe pedodiversity on a continental level and by different climatic zones. Subsequently, constructive comments on the work of IBANEZ et al. (1998) and in general on the concept of pedodiversity and its measurement were made by HUDSON (1998), ODEH (1998), VAN MEIRVENNE (1998), VEPRASKAS (1998), YAALON (1998), and WILDING & NORDT (1998). Several papers addressed the suitability of the concept in comparison to its development in the biodiversity context (CAMARGO 1999, IBANEZ & DE ALBA 1999) and in particular the role of the Shannon index as a measure of diversity (MARTIN & REY 2000, IBANEZ & DE ALBA 2000).

Subsequently to the discussion focussing mainly on the approach of IBANEZ et al. (1998) for the continental scale, CHEN et al. (2001) reviewed the work of IBANEZ et al. (1998) and made additional general comments on the concept of pedodiversity. MANZHI et al. (2003) applied the concept on a SOTER database in the Shandong Province of China for attributing different soil parent materials and terrain classes with diversity indices. PHILLIPS (2001) used the term pedodiversity in the context of intrinsic (independent of observable environmental controls) and extrinsic (dependent on observable environmental controls) factors in soil diversity. He developed a method for their relative importance based on soil-area relationships in an eastern North Carolina study area. On a broader area, AMUNDSON et al. (2003) used a GIS-based approach to quantify the US soil diversity and remaining undisturbed soils by analysing the density and abundance of soil series (USDA Soil Taxonomy 2003) in each state, and to quantify the land-use effects on soil diversity. Using the same State Soil Geographic database (STATSGO) GUO et al. (2003) studied the pedodiversity of the US on different taxonomic levels with an extended approach. They calculated pedodiversity indices (Shannon) and taxa area relationships for each level of the US Soil Taxonomy and compared pedodiversity of different geographical regions. In a regional approach with selected fine scale sampling areas, SALDANA and IBANEZ (2004) investigated richness, diversity and richness-area relationships of a soil sequence on the fluvial terraces of the Henares River (Spain) by use of three levels of the USDA Soil Taxonomy. Comparing different indices, they recommended the commonly used Shannon index as a suitable diversity measure. DEGORSKI (2004) emphasised pedodiversity as a part of geodiversity and discussed the spatial relationship with examples from central and northern Europe.

With respect to the basic comparability of biotic and abiotic diversity studies, the more applied context of pedodiversity was broadened by spatial analyses of the soil data in comparison to biotic assemblages. Regarding the pedotaxa-abundance patterns IBANEZ et al. (2005a) analysed pedodiversity-area relationships for islands (Aegan Islands). They found similar conformity to a power law as the ecological literature predicts for diversity area relationships in terms of the "Island Biogeography Theory" (after MACARTHUR & WILSON 1967; ROSENZWEIG 1995). Further applications of ecological methods were prepared by IBANEZ et al (2005b) for nested subset analyses of pedological assemblages. They showed that nested patterns of soils and soil assemblages at different scales could be described similarly to regularities in biotic assemblages. In a diversity related context, BOCKHEIM et al. (2005) applied the term 'endemism' on soils and showed that soil endemism occurs on broadly varying spatial scales. He emphasises the parallelism between ecological and pedological concepts.

Recently the application of pedodiversity studies on local to regional scales increased. PHILLIPS and MARION (2005) used pedotaxa-area relationships and the Shannon index to analyse the importance of biomechanical effects and lithological variations on pedodiversity on selected slopes in forest soils of Arkansas. PHILLIPS and MARION (2007) also tested a geomorphic parametric orientated classification system for the soil richness assessment. They proposed a presence absence scheme for six lithological and morphological characteristics of Arkansas soils in order to compare to the Soil Taxonomy. SCHARENBROCH and BOCKHEIM (2007) investigated forest pedodiversity applying Shannon diversity and evenness indices. Based on their results they strongly recommend diversity measure as an additional information in soil maps. TOOMANIAN et al. (2006) used pedodiversity indices (Shannon) to follow the trend of soil and landscape evolution in the central basin of the Iranian plateau.

The methodological debate about pedodiversity has recently been broadened by MCBRATNEY & MINASNY (2007) emphasising the incorporation of taxonomic distances in classification schemes to gain effective estimates for pedodiversity. They proposed the 'mean taxonomic distance' (Rao's quadratic entropy) as a good measure which combines both information of abundance and taxonomic distance between soil types.

With respect to the ongoing debate about the comparison of the 'soil-continuum dilemma' (IBANEZ et al. 2005) with its artificial classification structure and the biotic entities, IBANEZ et al. (2006) compared the mathematical structure of the USDA Soil taxonomy and a suborder of nematodes (see also IBANEZ & RUIZ-RAMOS 2006). They showed that pedological and biological classification conforms to power laws and are very similar from a statistical point of view. CANIEGO et al. (2006) analysed the self-similarity of pedotaxa distributions at the planetary scale with a multifractal approach (see also CANIEGO et al. 2007). They found a multifractal behaviour of soil pattern, which indicates a nonlinear chaotic dynamic in the development of soils.

The number of recent publications shows that the concept of pedodiversity is increasingly applied in Soil Science. However, as IBANEZ et al. (2005b) stated, the "…*quantitative studies of pedodiversity are in their infancy*…" and only very few authors are concerned with the implementation of abiotic parameters into the framework of habitat heterogeneity studies in ecology. Besides the reviewed approaches above, which are mainly dealing with the methodological suitability of the concept, the application of the concept to ecological studies could provide useful information for the further development of procedures. First practical applications of pedodiversity analyses in the development of new soil georeferenced databases and soil information systems are already established (e.g. the European soil database, FINKE et al. 1998). Recently, the opportunity of the application of pedodiversity indices is also discussed in the context of a new soil assemblage classification system in Germany (SCHMIDT & JAHN 2004).

At the same time, the suitability of the concept is still in discussion. Therefore, one should bear in mind the main aspects of the definition, possibilities, restrictions and open questions in terms of pedodiversity. The focal points of the discussion in pedodiversity literature are summarised below.

Aspects and potential applications of pedodiversity:

The concept of pedodiversity is discussed very controversially, both, the term itself and the applied methods and scales. In his comments of the manuscript of IBANEZ et al. (1998*)* ODEH (1998) formulated pedodiversity as the *"variability of soil in a specific area or region, as determined by its constitution, types, attributes and the conditions under which the various types were formed"*. IBANEZ & ALBA (1999), however, considered that any type of pedodiversity needs a specific definition according to the questions to answer. Thus, pedodiversity and its measurement under consideration of the outlined aspects have to be defined. IBANEZ (2005a) summarised the main approaches for pedodiversity analyses as follows:

- Genetic pedodiversity (diversity of genetic horizons)
- Taxonomic diversity (diversity of soil classes)
- Parametric pedodiversity (diversity of soil properties)
- Functional pedodiversity (soil behaviour under different use)

The application of the different measures for the quantification of pedodiversity is related to specific questions in different contexts. In a former study, IBANEZ et al. (1995) outlined some potential uses of pedodiversity indices:

- Quantification of the pedological richness and evenness of a certain area (e.g. for determining preserving areas)
- Determination of the heterogeneity of soil associations or mapping units
- Estimation of the loss of information when generalizing profile data to maps
- Determination of the genetic variability within a particular unit by the consideration of the number and thickness of genetic horizons

This short list of potential applications shows already that measuring pedodiversity is more than an academic exercise and that the indices provide a new tool for attributing soil assemblages and the analyses of soil related questions. E.g., the second point of the listed applications (heterogeneity measure) can be related to the above introduced concept of soil regionalisation. As an example, the lowest hierarchical mapping unit, the pedotop might be qualified by one or more indices of diversity, which could qualify its heterogeneity by a single number. Although a quantification of heterogeneity is already established by other abbreviations or statistical values in numerous contexts, the methods of pedodiversity might provide the closest link to the biotic system as it uses the same methods and has an integrative character.

HUDSON (1998) mentions that pedodiversity studies build one step against the deficiency in diversity studies which have focussed almost exclusively on the biotic components of habitat heterogeneity. This point of view is corroborated by VAN MEIRVENNE (1998) who regards the concept of pedodiversity as a possibility to reach a more holistic understanding of the planet.

The above outlined aspects and potential uses of pedodiversity are all soil related issues which are not discussed in their importance for Soil Science. The following discussion about the suitability of the concept rather focuses on the new methods applied in pedodiversity and whether they are able to provide information which could not be gained by other established methods.

Suitability of biodiversity measures for pedodiversity

The most conspicuous difference of soil diversity and diversity of biotic components with a distinct species concept is that soil builds a continuum, having properties that vary predominantly continuously with depth and horizontal distance. This is often seen as a barrier for the application of ecological diversity measures which are based on the species concept (IBANEZ 1995). VAN MEIRVENNE (1998) states that intergrades in biotic populations between living organisms are rare, whereas in soils this is rather the rule than the exception. However, also the species concept represents only one level in the range of the entire biodiversity and shows shortcomings with regard to taxonomic distinctness (HARPER & HAWKSWORTH 1994). In terms of plant communities or vegetation types with gradual, fuzzy changes, the system becomes even more arbitrary while it is still used for diversity studies. Moreover, the breaking of a continuum into discrete classes to deal with is a common tool, not only in the Soil Sciences, and often the only possible method in ecology to classify the studied object (e.g. climatic zones).

As a general restriction, CAMARGO (1999) pointed out that biotic factors which influence the biodiversity such as competition, predation and parasitism do not exist in the abiotic environment. Undoubtedly, these striking differences might underline different evolutive mechanisms and dynamics of the two systems. However, although the soil is essentially a product of deterministic factors and processes and not part of an evolution like the biotic system (YAALON 1998), the tools and concepts for measuring biodiversity (e.g. indices of richness, evenness and diversity) are well applicable for the description of pedodiversity (MARTIN & REY 2000, IBANEZ & DE ALBA 2000). The simplest rationale is that these indices are suitable for description of any population which can be subdivided in different classes. In addition, ecology "borrowed" the concepts of diversity indices from information theory.

Another argument for the justification of pedodiversity measures is the occurrence of similarities between the biotic and abiotic natural system. Based on the results of available pedodiversity analyses, IBANEZ and DE ALBA (2000) assume that pedodiversity-area-relationships should follow power laws or logarithmic distribution as known for species-area-relationships. This was confirmed by PHILLIPS (2001) and IBANEZ et al. (2005a, 2005b). IBANEZ et al. stated that abundance distribution patterns of pedotaxa follow similar trends to those of biotaxa. This strengthens the arguments for the application of the same toolbox for diversity measures, as the systems show similar trends. However, the underlying mechanism and causalities are still to identify, i.e. are these trends arbitrary by application of similar classificatory approaches or a natural trend.

Shortcomings of classification systems in pedodiversity

Besides the general problem of breaking the soil continuum in arbitrary classes, criticism also arose in context of the taxonomic diversity applied by IBANEZ et al. (1998) in their analysis of the world pedosphere using the FAO world's soil map and major soil groups. HUDSON (1998) argued that a generalisation of the databases could considerably reduce the information about the diversity . A further restriction is that soil classification systems such as the FAO, although including pedogenetic criteria, are mainly designed for agricultural purposes and biased towards the temperate zones. Thus, in areas where agriculture is marginal (e.g. the arid climatic zones) soil classifications and soil maps typically describe the pedosphere in less detail (VAN MEIRVENNE 1998). Especially the low richness of the arid climate zone in the study of Ibanez could be due to the low number of studies in these regions and the shortcomings of the FAO classification system to describe the variability of arid soils (IBANEZ et al. 1998). YAALON (1998) found a very low reliability of the FAO soil map for arid and tropical regions in Africa. VAN MEIRVENNE (1998) addresses criticism at the differing within-class variance and questions the equal weight entry of major soil groups in diversity analyses.

Therefore, as classical diversity analyses are strictly bound to calculate with discrete units, pedodiversity analyses always depend on the quality of the applied classification system and the underlying data. This includes the taxonomic distinctness of the classes as well as the "position" of a soil unit within a taxonomic class. As SALDANA and IBANEZ (2004) pointed out, both field and lab data may change pedodiversity calculations by hierarchical restrictions in the classification system or slightly differences in the lab data. This can lead to an "artificial" increase in pedodiversity.

Nevertheless, the existing databases and the current classification systems are the best available and rough estimates are better than no information when one bears in mind the constraints of the results. In the context of their pedodiversity analyses using FAO major soil groups, IBANEZ et al. (1998) state that it is not "*an excuse to delay analyses of the available data*" which was agreed to by WILDING and NORDT (1998). Additionally, the discussion showed that many points of criticism are often rather related to questions on the quality of the classification systems and the current soil survey paradigm (see HUDSON 1992) than to the suitability of the diversity indices in general.

Since the pedodiversity approaches only used taxonomic classifications (national or international systems), MCBRATNEY (1995) raised the importance of pedometrics for the future research of pedodiversity. Some authors (e.g. ODEH 1998, VEPRASKAS 1998) see pedodiversity and spatial variability of soil properties as synonymous concepts. In contrast, IBANEZ & ALBA (1999) see the two approaches as independent and complementary concepts as both can express different information. FINKE et al. (1998) use diversity as a measure for heterogeneity of taxa and variability as a measure for the variability of soil properties or parameters. In a case study, SALDANA and IBANEZ (2004) showed that diversity of certain soil properties and taxonomic diversity are negatively correlated. However, this problem can be simply solved when the context of a pedodiversity research is well documented. At the same time, it is an opportunity to express different aspects of pedodiversity as outlined above.

IBANEZ et al. (1996) recommended a continuous use of the established ecological methodologies because they offer the best possibility to speak a similar language as the ecologists in environmental sciences. At the same time, he saw the opportunity of incorporating pedometrician research in terms of detailed spatial investigations and by methodological work to establish models and indices which combine the spatial variability and the traditional ecological diversity concept.

6 Quantification of pedodiversity for the study areas with different approaches

6.1 Introduction

The previous chapter pointed out that the application of indices and models used in biology is in an initial phase in pedology. Many further studies will be necessary before the analysis of the potential and the limitations of these methodologies will be grounded sufficiently. Pedodiversity analyses might be powerful tools in environmental management and assessment. There are opportunities not only in their application when designing a network of soil reserves with the same tools employed in conservation biology, but also as an indirect estimator for regional biodiversity when biotic data is limited or not available. However, further work on pedodiversity requires more complete data sets at finer scales (IBANEZ et al. 1998).

One aim of this study is to use the standardised fine-scaled soil database for an assessment of pedodiversity with both, the established ecological indices, which were already employed by different authors mentioned before, and by the setup of new methods.

In chapter 3, a complete overview of the surveyed observatories is given. This includes the overview of the spatial distribution of the soil units, variation in selected parameters and the description of reference profiles. The following chapter now aims at a synthesis of the available soil information per observatory in single values or indices, which can describe the pedodiversity of a single observatory and allow the comparison of different sites.

Compared to the Pedodiversity studies described in the literature review (see chapter 5.4), in this study the pre-conditions are quite different:

- The pedodiversity has to be quantified on a relatively small scale, i.e. for an area of 1 km^2
- The indices are always related to the same area of ‘total population’ (1 km^2)
- The inter-area comparison of the pedodiversity indices will be applied on a relatively large scale (> 2,000 km) including a strong climatic gradient and the bordering of the Paleotropis to the Cape floral kingdom
- The quality of the data, i.e. the number of profiles and quality of laboratory analyses, is comparable for all sites
- The possibilities to compare derived pedodiversity indices with biodiversity data are provided by the standardised procedure applied in the project, which ensures a spatial linkage of the data.

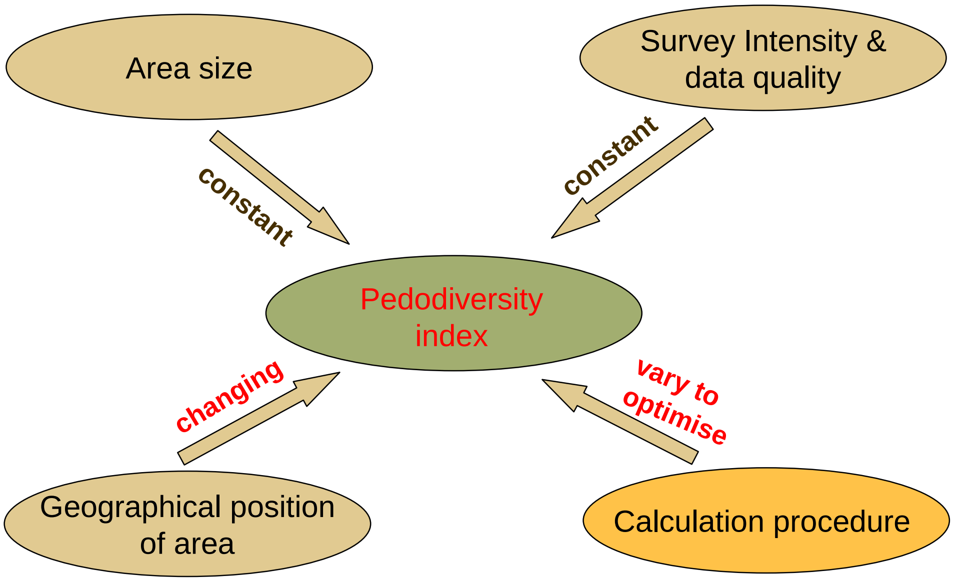


Figure 205 Scheme for the pedodiversity analyses in this study

Figure 205 illustrates the background of the database and the applied concept of the study. By the constancy of the surveyed areas (1 km^2) and the survey intensities (i.e. number of profiles), the creation of a pedodiversity index for a single observatory by a certain procedure is possible. With regard to the investigated region (drylands of southwestern Africa) and included data, the study aims to optimise the "procedure of calculation". With the completed pedological data set it will be possible to combine and compare various pedodiversity indices derived from numerical values as well as from classified soil units. While the soil units can be used for the derivation of a "taxonomic" pedodiversity, the selection of soil properties, which have an important influence on ecological processes, allows the development of a parametric orientated index of pedodiversity.

The aims behind these approaches follow several tasks and are listed below.

- The reliability of distinguishing sensitivity according to a broad international classification such as the WRB on relatively small areas of 1 km^2 shall be tested.
- Within the different approaches, an evaluation with respect to sensitivity and analyses intensity shall identify the 'best average method' for further pedodiversity measures (i.e. simplification)
- The generation of an integrative value for soil diversity, i.e. a single number which characterises the overall variability of ecological significant soil properties
- Comparison and analyses of biodiversity data to improve the knowledge of the interaction and causalities between pedo- and biodiversity

Besides the focal aim of generating pedodiversity indices to derive an abiotic diversity measure which can be compared with biodiversity data, further topics emerged during the study which shall be proofed additionally. One subject is the applicability of the WRB-classification system for the description of soil heterogeneity on such a small scale as applied here. A second topic is the development of other approaches to derive pedodiversity indices and to identify the easiest approach that would give reliable results. The unique possibility to combine high quality abiotic and biotic data derived with standardised procedures in the project enables correlation analyses with biotic data. Here, a focus will lie on the diversity of higher plants (phytodiversity), i.e. correlation analyses with respect to richness and evenness between soil and species data along the transect as well as generation of 'soil unit area curves' for soil units in each observatory as a basis for comparative analyses with phytodiversity.

Three different approaches for the calculation of pedodiversity indices have been found to be applicable on these data sets and will thus be tested in the following chapters.

1. Taxonomic pedodiversity classified based on WRB-units (profile data)
2. Parametric pedodiversity classified based on 'soil-eco-types' (SET) (topsoil & profile)
3. Parametric space ('environmental envelope') by calculation of the n-dimensional space of normalised soil properties (topsoil & profile)

Figure 206 illustrates the procedures in each of the three approaches. Whereas the first method is comparable to the pedodiversity approaches cited in the literature above (e.g. IBANEZ et al. (1998) amongst others), the approaches 2 and 3 are newly developed in this study. These approaches are tested for both, using the complete soil profile and solely the topsoil information (0 – 10 cm). The comparison of both variants will allow an answer to the question, if the soil data set can be restricted to topsoil data without ineligible lost of pedodiversity information. In total, a number of 32 pedodiversity data sets, including different measures, will be produced with the three approaches[1].

[1] WRB with three qualifier levels = 3, Parametric classification with 5 class systems, each for profile, topsoil, and profile without root.-space = 15, Parametric space with convex hull and cubes = 14

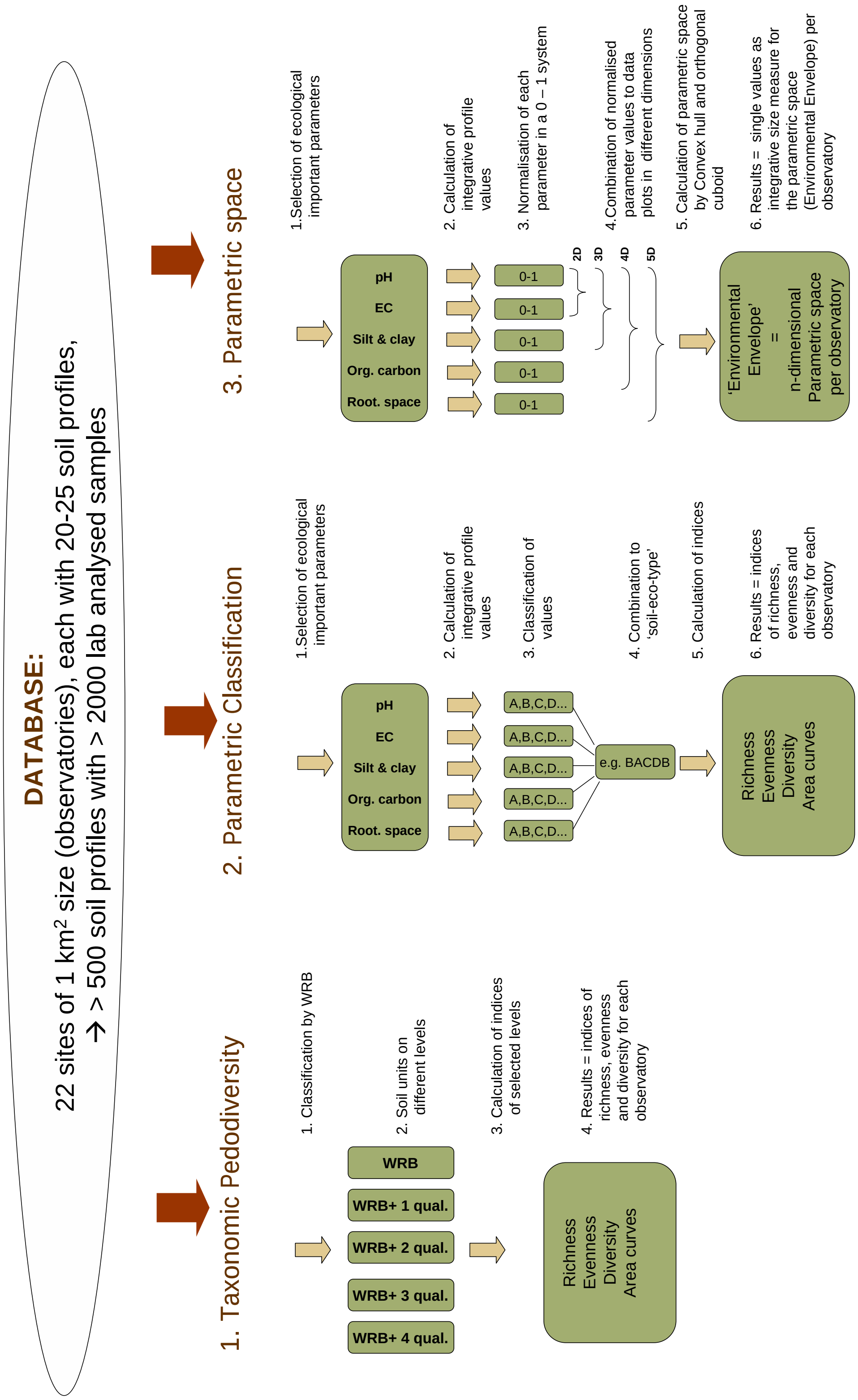


Figure 206 Scheme of the methodology in the three different pedodiversity approaches

Tab. 6 gives an overview for the available data with regard to the different pedodiversity approaches. The overarching aim to gain a number of 25 profiles per observatory is not always reached due to various difficulties (mainly constraints of field work periods). The lacking profiles are partly reconstructed for the WRB-classification by use of topsoil samples and the topographical position in the observatory.

Although few observatories are reduced with regard to available data, the database comprises sufficient information for the planned development and application of pedodiversity indices as well as comparative analyses with phytodiversity data. The presentation of the data in this overview serves as an opportunity for the reader to compare the following results with respect to data input.

Tab. 6: Overview of the available soil data for pedodiversity analyses. Unmarked: n = 25; marked orange: 25 > n > 19; marked yellow: n < 20

	Method 1	Method 2 & 3	
Obsnr	WRB	Profile	Topsoil
1	19	7	19
2	24	24	24
3*	12	12	12
4	25	25	25
5	25	25	25
6	25	25	25
10	22	17	22
11	22	17	22
16	20	20	20
17	25	25	25
18	25	20	25
20	25	25	25
21	15	6	15
22	25	25	25
24	25	25	25
25	25	25	25
26	25	16	25
27	25	17	25
32	25	15	25
33	25	25	25
39	25	25	25
40	25	25	25

* by transect analyses

6.2 Pedodiversity based on taxonomic classification according to WRB

6.2.1 Introduction

The taxonomic pedodiversity index is based on the classification system of the WRB (FAO 1998). The main principle behind this approach is to regard the different soil units like species in biology. By this, different analytical methods like number of soil units, diversity and evenness measures per observatory are possible. These values can be calculated and compared for each observatory along the transect.

6.2.2 Methods

The results of a taxonomic classification depend on both, the quality of field and lab data, but also the equality of the applied classification level. In this study, the WRB (1998) with a maximum of four qualifiers was applied to all included profiles. However, frequency distributions showed that already with two qualifiers the maximum differentiation between the profiles is fulfilled (Tab. 7). That means that the additional qualifiers provide additional information on the single profile, but are not needed as a further separation tool. This result indicates a correlation of qualifiers which is true for the studied area but not in general for the WRB system. As Tab. 7 depicts, the 509 used profiles distribute on 11 of the 30 worldwide possible reference groups (WRB 1998) and on 125 soil units by the use of two qualifiers. This already gives an impression of the soil diversity along the transect.

Tab. 7 Number of soil units within the entire database for the transect observatories

	Ref.- groups	Ref.- groups with 1. qualifier	Ref.- groups with 2. qualifier	Ref.- groups with 3. qualifier	Ref.- groups with 4. qualifier
N (509 total)	11	62	125	125	125

Figure 206 (left column) gives an overview of the applied method for the taxonomic diversity analysis. The single steps can be explained as follows:

1. Classification of the entire database (509 profiles) with the WRB (1998)
2. Separation of the results in several levels of differentiation: i) WRB reference group, ii) 1st- qualifier level, iii) 2nd- qualifier level, iv) 3rd- qualifier level, and v) 4th-qualifier level.
3. Each differentiation level is used for the calculation of richness, evenness, and diversity indices as well as for creating ‘soil-unit area curves’ for each observatory
4. The resulting indices and curves are used for the documentation and comparison along the transect.

6.2.3 Results

With the description of the observatories (chapter 3 and chapter 4) it should be pointed out, that the WRB classification methods applied to the soils of a single km^2 are fairly sensitive and thus able to describe soil variability to a high degree. In Figure 207 the comprehensive results of soil classification along the transect are shown in three different hierarchy levels of the WRB. Except for two observatories (#01, #32) two to six reference groups are found. Especially the case of #24 with 6 reference groups highlights how diverse an area of one square kilometre (which was not selected with the aim of a maximal heterogeneity) can be with respect to the soil units. The increase in the number of soil units by adding one or a second qualifier underlines the sensitivity of the WRB in delineating differences on small scales. The increases also pronounce the necessity of detailed classification on the 2^{nd}-qualifier level to use the strength of the WRB. Highest soil unit numbers are found in the arid part of the winter rainfall region (Namaqualand), followed by the central Namibian savanna observatories. The lowest numbers occur in the observatories on dune sands, e.g. in the Kavango (#01,#02), the Kalahari (#17) and the costal plain west of the Richtersveld (#21).

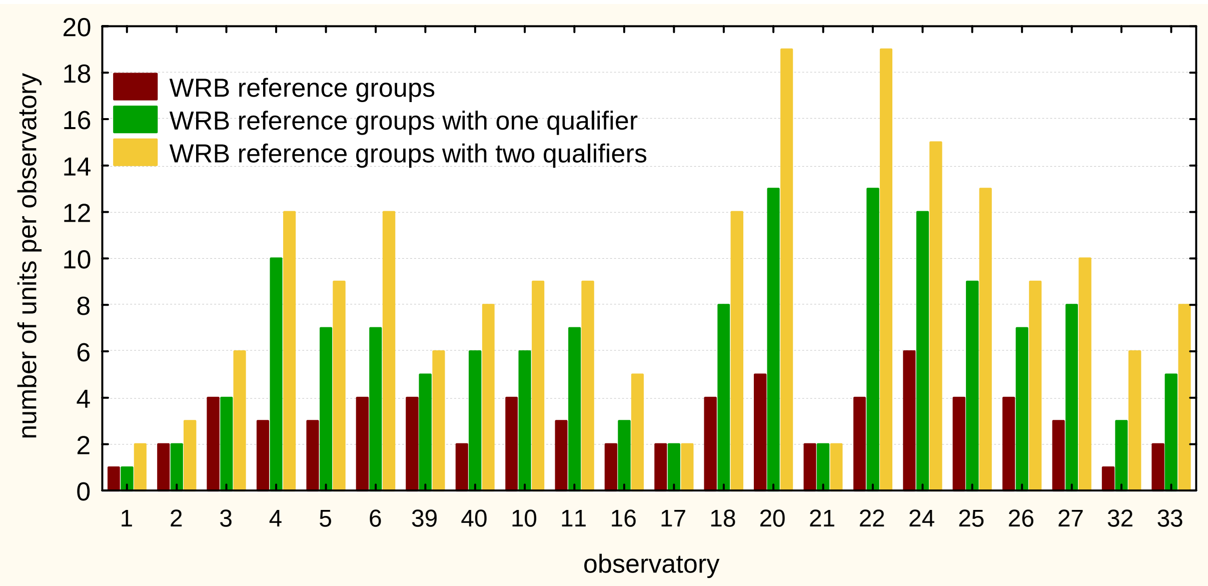


Figure 207 Number of soil units per observatory along the transect. Different colours indicate the different classification hierarchies of the WRB classification system (Ranking 1-25)

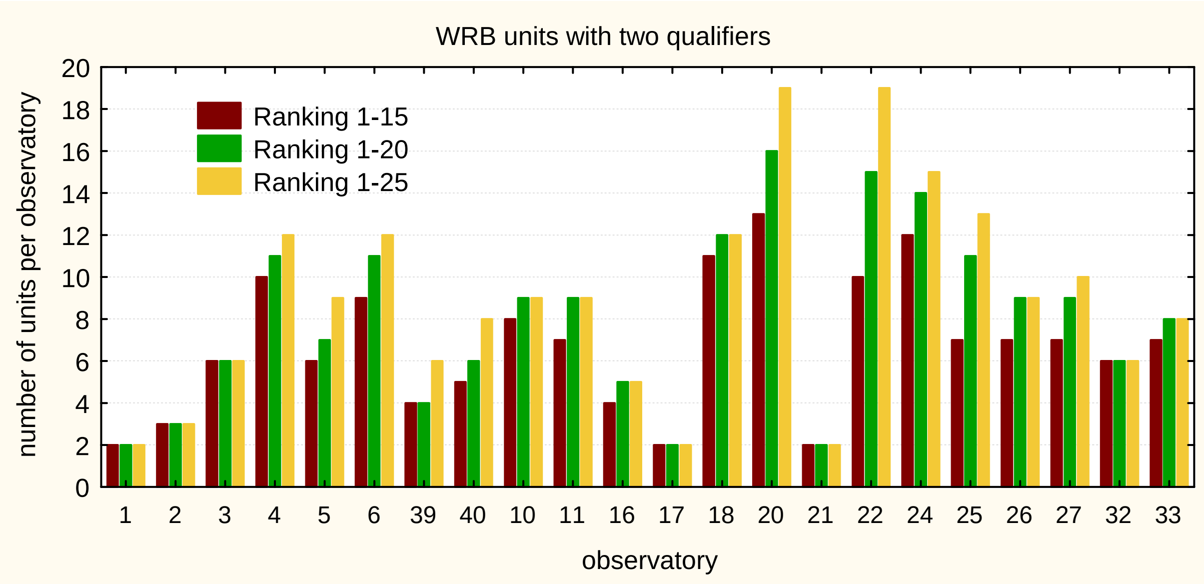


Figure 208 Number of soil units (2nd-qualifier level) per observatory along the transect. Different colours indicate the different incorporated rankings

Besides the difference in applied classification levels, the ability of all methods used in this study to indicate the entire pedodiversity of an observatory is dependent on the amount of included profiles in the data basis. To test this influence on the diversity (here richness) results, in Figure 208 the effect of survey intensities ranging from 15 over 20 to 25 profiles km^{-2} is depicted. Whereas the dune sand observatories (#01, #02, #03, #17, #21) stay constantly low in their number of soil units with increasing number of profiles, especially the winter rain observatories of the Namaqualand (#22, #24, #25, #27) and also those of the central Namibian savanna (#04, #05, #06, #40) show a strong increase of up to five new units for 5 added profiles.

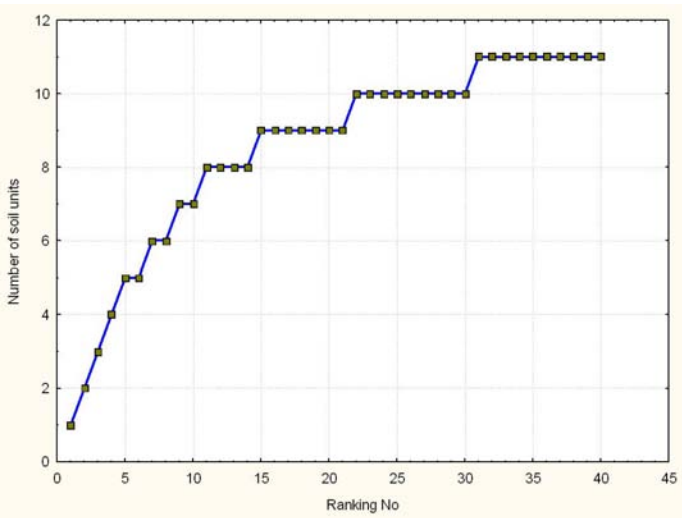


Figure 209 ‚Soil unit-area-curve' of WRB soil units (1998, 1st qualifier level) of obs. #04 (Omatako)

An example for a 'soil unit area curve' for the observatory #04 (Omatako) which was selected for an intensive survey up to ranking 40 is provided in Figure 209. Here the increase of the first qualifier level units is shown with the number of examined plots. For this observatory it could be shown that the probability to find soils with a different classification is substantially decreasing if the number of investigated positions is higher than 15. However, the increase of soil units trough broadening data base differs with the study regions. To demonstrate this, in Figure 210, the increase in taxonomic pedodiversity for all observatories, based on 2nd level classification of the WRB, is shown. Although each line has some specifics, some typical courses can be recognised: i) observatories with low pedodiversity reach the level of highest soil unit numbers (e.g. obs. #02) very fast, ii) observatories with medium pedodiversity reach only small further increase in ranking number between 15-25 (e.g. obs. #18), and iii) observatories with a high pedodiversity show strong increases without or with only a slight reduction of soil unit increases in high ranking numbers (e.g. obs. #22)

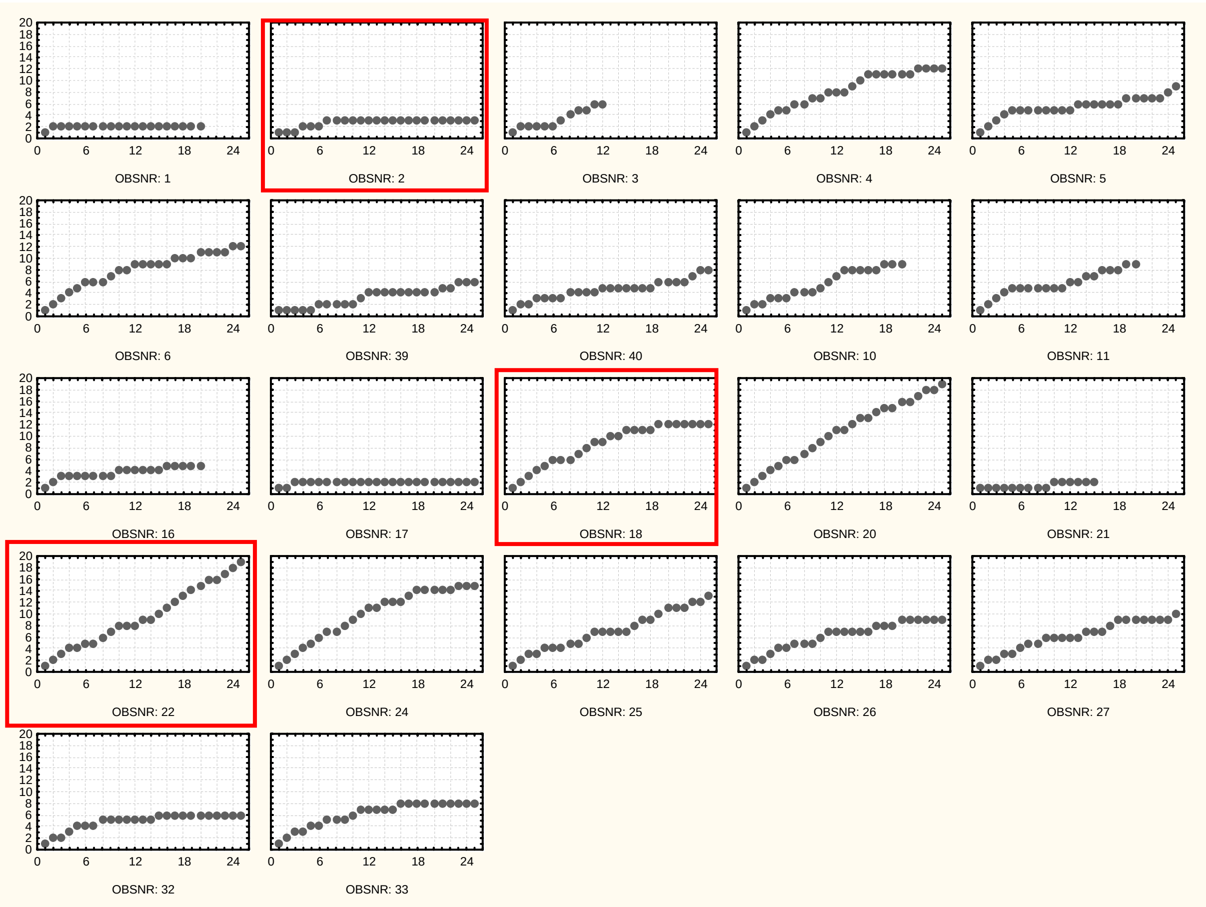


Figure 210 'Soil unit area curves' for each studied observatory along the transect (WRB 1998, 2nd qualifier level) (x-axes = ranking numbers; y-axes = number of soil units)

Based on curve interpretation of this data it can be concluded that with a number of 25 profiles per km^2, selected according to the BIOTA ranking procedure (see chapter 2.1), in 11 (50 %) sites the pedodiversity is suspected to have been captured (almost) totally, for 8 (35 % of areas) we suspect a 75 to 90 % finding and for 3 (14 % of areas) the increase of soil units with additional data might be larger than 25 %. For the proper and comparable description of soil diversity of different areas in the drylands of southern Africa using the strength of the WRB, at least 25 soil profiles are needed.

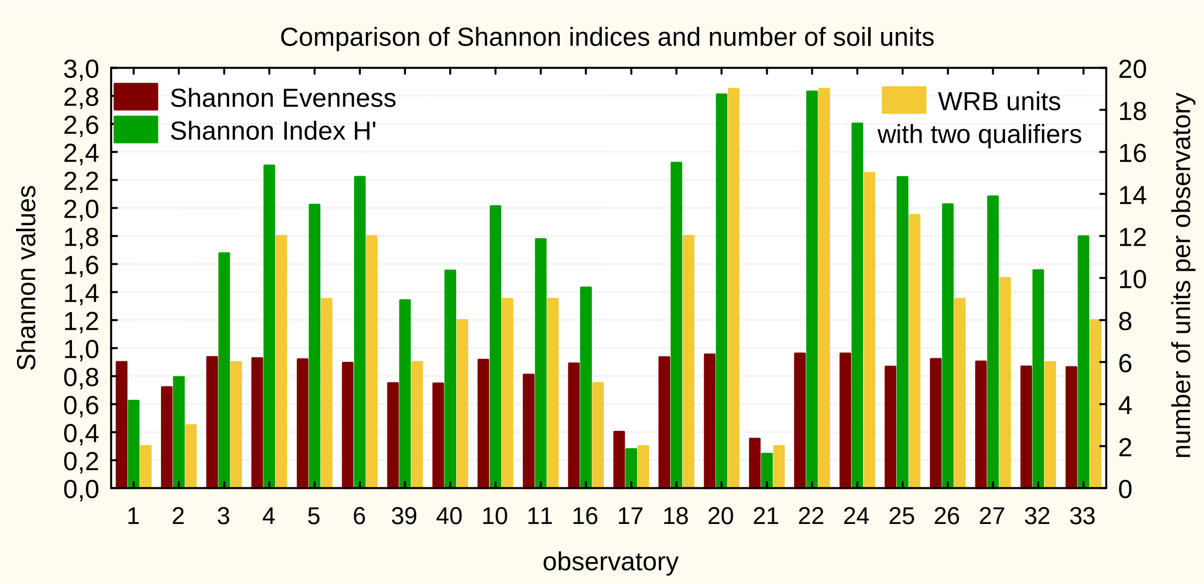


Figure 211 Number of soil units, Shannon Evenness and Diversity index per observatory

In Figure 211 the WRB soil unit numbers as a measure of richness are compared to the calculated Shannon diversity index H’ and the Shannon evenness index. The strong correlation between the soil unit numbers and the Shannon index gives an impression of the richness dominance in the Shannon diversity index. Evenness values are very high (almost 1.0) in the various areas which is an effect of the near singularity of each soil unit (#20 and #22) or a real even distribution in lower number of soil units (#18). The lowest values are found in the dune sites #17 and #21 where a nearly homogenous soil structure occurs but single “azonal” profiles lead to a low evenness value. Most values are around 0.9 indicating a relatively even distribution. Slightly decreased values of 0.7 are found in #02, #39 and #40 where few single unique profiles occur in a relatively even distribution of the other occurring soil units.

This example shows the strong influence of richness on the Shannon diversity index H’. It is therefore recommended to use the single richness information with an added evenness value to give the most precise information on the system. This is also true for the parametric classification results, which are in comparable dimensions of the total numbers of soil units or soil-eco-types respectively. Otherwise there is a loss of information. The comparison of #18 and #25 creates an example for this case. Although inhabiting lower soil unit numbers, #18 shows a higher diversity index than #25 due to its even distribution, which is incorporated positively in the integrative Shannon index.

6.2.4 Discussion of the taxonomic classification approach

The taxonomic classification according to WRB revealed a good sensitivity for the expression of the soil variety on the level of one square kilometre as well as for comparisons along the transect. The most important advantage of this approach is the application of an international accepted classification system that is easy to communicate.

Disadvantages of this approach are evident due to the ‘inequality’ of the classification system, which uses both, genetic and parametric aspects in the delineation of soil units. Genetic aspects are often of minor importance for the current ecological properties of a soil unit. The same is true for a number of soil properties or diagnostic horizons. Additionally, the distances in parametric criteria are unevenly distributed across the different reference groups. A further and common problem in class defined systems is that even small variations close to class borders can increase the resulting number of soil units, although overall ranges in properties are small and would not have an effect if occurring at another position within a class. This would lead to an arbitrary diversity.

The above-mentioned aspects are explained by the following example: Comparing a Eutric and a Dystric Arenosol can result in very different ecological values and is therefore a good differentiation with respect to site conditions. On the other hand comparing a Chromic Cambisol and a Rhodic Cambisol can result in more or less the same site conditions. Both cases give the result of two soil units.

Despite knowing the shortcomings of the WRB (mix of genetic and parametric properties, unequal class sizes in parameters), the soil units are used here to analyse taxonomic pedodiversity. We argue this with: i) experiences made in further studies noted the restrictions of taxonomic pedodiversity, but also showed that it can be a powerful tool in analysing pedodiversity, especially in finer scaled approaches and by using the more differentiated lower hierarchical units of a classification system ii) we found in the highest hierarchical level already up to 4 reference units on a square kilometre, which shows that the system is sensitive enough to structure the soil and should be more precise on the lower level units iii) as it was outlined in the chapters before, diversity studies are producing single numbers to compare whether one system is more diverse than another. However, the results are dependent on the applied classification. The application of an international system allows an interpretation of the results by external scientists and will, in the long run, enable a comparison with other studies.

The calculation of the established ecological diversity indices like the Shannon H' reveals a strong correlation with the soil unit number, as it is richness dominated. Relatively low number entities like in this study lead to this effect. In such data sets, the interpretation according to the Shannon index thus provides no advantage with reference to the single interpretation of soil unit numbers and a separate interpretation of the evenness to gain additional information about the data structure. The evenness index provides useful information about the frequency of occurring soil units. It is therefore recommended for further use. However, the frequency pattern behind the values has to be introduced in advance to interpret the difference between e.g. a value of 0.7 and 0.4.

6.3 Pedodiversity based on parametric classification

6.3.1 Introduction

Soil classification systems like the World reference base (WRB, FAO 1998, 2006) often incorporate both, genetic and parametric interpretation. This mixture is valuable for international understanding and also for agricultural purposes. However, the applied criteria are often unequal in precision, the derived units differing in size and the rankings of the soil features are arbitrary. In describing and comparing areas, this leads to pedodiversity indices that are to an unknown part reflecting genetic features without actual ecological importance (e.g. a certain colour). In analysing river terraces of different ages, SALDANA and IBANEZ (2004) e.g. showed that the diversity of soil properties (parametric) and taxonomic diversity where negatively correlated. Although this trend is depending on the selected properties and landscapes, it shows how carefully one has to be with the results of diversity analyses with respect to further interpretation.

One helpful method to quantify ecological relevant pedodiversity might therefore be a grouping of the studied objects according to a new system that is solely based on quantified soil properties of ecological relevance. Despite the fact that the application of such a new system will produce only abstract names for soil units (in the following called ‘soil-eco-types’ SET), which allow to calculate indices of richness, evenness and diversity, the strictly parametric database will probably allow a more precise ecological evaluation and grouping of the objects. The question, if this type of grouping of soil diversity will have more explanatory power, will be evaluated in chapter 7 explaining the correlation between taxonomic, parametric and biological diversity indices.

6.3.2 Methods

The basic principle in this method is to select a number of ecologically important soil parameters and to define useful and preferably even sized classes for each parameter. This way each single profile can be classified, for which there are values for all included parameters. By combining the classes of the selected parameters, a new identifier for a “soil-eco-type” is created which can be used for analyses like a WRB-soil-unit or a species name. Figure 206 (centre column, chapter 6.1) gives an overview of the applied method for this parametric classification diversity analyses. Each step is explained in the following section.

1. Selection of ecologically important parameters: With this first step, the inclusion of soil properties in the procedure is decided. The selection should include those quantified soil properties, which are known to have a strong impact on the occurrence of organisms (plants, soil organisms) and which are in general statistically mostly independent. Here the parameters pH-value, EC, silt & clay, org. carbon and rooting space have been chosen. This first step bears the highest potential to influence the results. Each scientific approach has its own assumptions, which are important parameters depending on the question behind the study and existing knowledge. E.g. the investigation of grassland productivity would focus on nutrient and water availability, while in arid and semi-arid regions the most critical factors for plant growth, apart from water, are salinity and alkalinity. For the mostly natural vegetation of arid and semiarid rangelands this study focusses on, the importance of different soil properties for the support of plant growth is not known precisely. Therefore, I tried to identify the most important soil parameters for plants in a natural system and selected the following five

- pH-value: used as a "master variable" in soil science, determining microbial transformation, nutrient availability as well as root- soil- interactions.
- EC: like the pH-value an important parameter for the overall characterisation of site properties. In the lower range, the EC can be interpreted with regard to the soil chemical ion status, in the higher range EC indicates the degree of salinity.
- Silt & clay content (SC): soil texture can be regarded as the "physical master variable" for the overall characterisation because it is the main factor for the pore size distribution that drives the air and water supply. However, soil texture is not usable as a single parameter in a cardinal scale, which is required in a parametric classification system. Therefore, here the sum of silt and clay is used as an alternative parameter. Especially in semi-arid and arid systems, evaporative losses as well as infiltrability of rainwater are affected by these fractions and thus the local soil aridity increases with rising clay & silt percentages.
- Organic carbon (OC): this parameter is also important for the overall characterisation for both, soil physical structure and soil chemical properties (nutrient pool, CEC). Compared to the pH, EC and texture this parameter can be regarded as less important. However, besides its direct importance for the soil system it can be used as a marker of long-term processes and dynamics in the soil that are not directly measurable.
- Rooting space (RS): this parameter is chosen due to its importance for the soil resource availability (i.e. fine earth volume), esp. if shallow soils on underlying bedrock have to be compared to soils on deeply developed fine earth. Difference in the rooting space can be directly linked to the availability of water and nutrients and is therefore an import factor to look at. The RS is limited by bedrock, crusts and the content of coarse fragments.

Theoretically, the selection of ecologically important soil parameters may include higher numbers than the above chosen. However, with the planned classification of each parameter the number of the resulting soil-eco-types increases exponentially.

By enlarging the number of parameters and by decreasing the class sizes it would be possible to develop a system, which is sensitive enough to separate almost every profile into a single "soil-eco-type". However, aiming at a system that enables the best differentiation between the most homogeneous and the most heterogeneous sites, the further addition of parameters is not useful for the application in this study.

Tab. 8 Examples of possible soil-eco-type cases by different number of classes and parameters

No. of classes (C)	No. of para-meters (P)	No. of theoretical cases (N)
6	5	7776
5	5	3125
4	5	1024
3	5	243
2	5	32
1	5	1
6	4	1296
5	4	625
4	4	256
3	4	81
2	4	16
1	4	1

The table above gives examples of the number of theoretical cases for four and five parameters with a class number from one to six. The number of possible types (N) can be calculated with $N = C^P$ (C= number of classes; P= number of parameters). Additional parameters would strongly increase the number of possible cases. To result in a reasonable number of possible cases it would then be necessary to reduce the number of classes. It is therefore important to find the balance between the number of parameters and the numbers of classes, which enables a sound system.

2. Calculation of integrative values: An inherent problem of an overall parametric soil profile characterisation is multiple information across the different horizons. To produce e.g. a single pH-value for a profile it is most appropriate to integrate all measured values across a certain depth. Here, this is achieved by a weighted average calculation for each selected parameter for a) topsoil (0-10 cm) and b) profile (0-60 cm).

3. Building classes for each parameter: For each parameter in the system a classification has to be defined that allows the categorisation of a single soil parameter value. Upper and lower class borders were chosen after a check of the entire data set in this study to allow maximum sensitivity. Silt & clay content and the rooting space both cover a range of 0 – 100 % which are applicable in other regions as well. The resulting ranges for pH, EC and organic carbon are fitted to the data set. However, due to the wide ranges along the transect, these classes would fit for most other regions worldwide as well.
4. Combination of classes resulting in a new "soil-eco-type" (SET): After the affiliation of an integrative value to a class, the class identifier of each parameter (A, B, C, D,…) can be combined with an eco-type identifier for each profile, e.g. "ACAB" (topsoil) or "ACABD" (profile). This arbitrary abbreviation can be used as a name for a SET that is strictly based on classified parametric values. Thus, this SET classification provides a single name for each profile as taxonomic systems like the WRB do.
5. Calculation: Analyses by number of occurring soil-eco-types and diversity indices. Each differentiation level (i.e. class system) is used for the calculation of richness, evenness, diversity and area curves for each single observatory.
6. Results: The results can now be used for the documentation and comparison along the transect.

This general scheme is applied in 15 variants resulting from 5 approaches using different class numbers times 3 variants on the soil dataset (i)only topsoil, ii) averaged profile data, iii) averaged profile data without RS).

The class limits for the selected parameters have been defined according to the following principles:

- pH: equally sized classes are chosen as the easiest and most applied system to describe the H^+-concentration with the pH-value.
- EC: classes for the electric conductivity are based on different log-scales or class borders that are near to log-scale behaviour. The reason for this decision is that the $EC_{2.5}$ includes two ways for interpretation (explanation see selection of parameters above). In the partly very nutrient-poor areas along the transect it is important to distinguish different classes with small ranges like 20, 40 or 240 µS cm^{-1}. If the EC reach values > 300 µS cm^{-1} the nutrient aspect of the EC is of decreasing importance and the salinity aspect increases. As in soil salinity ranges in EC of 1 - 15 mS cm^{-1} are important with respect to the strength of salt stress, I decided to use wider ranges in the higher classes of EC.

- Silt & clay-content: as analysed data of silt & clay contents do not exist for all horizons, the classification of this parameter has to take the pre-classification resulting from the finger test of the texture (KA4, KA5, AG BODEN (1994)) into account. In the highest degree of differentiation, namely the 6-classes approaches, the classes are thus aggregated on the following textures: pure sands < slightly silty, clayey and loamy sands < silty, clayey and loamy sands < sandy loams and sandy clays < slightly sandy loam and silt < loamy and clayey silt, loamy and silty clay. In the 4 classes approach the classes are reduced to: sands < loamy substrates < loam substrates < silt and clay dominated substrates. In case of existing texture analysis the sum of silt and clay was used.
- Organic carbon: for the 6 class approaches a $\log_2$ based system enables the differentiation of small differences in the lower classes and broadened ranges in the higher classes. The reason for this decision is a sensitivity of the soil ecological behaviour in areas with very low, but also significantly different organic carbon contents in different habitats. In regions with higher contents, it is not necessary to distinguish such small classes; therefore, the classes here are broadened.
- Rooting space: the calculation of the RS is done in percent portions of the maximum rooting volume of 1 m^3 = 100 % (1 x 1 x 1 m). For the reduction of the RS the occurrence of bedrock, massive silcretes or calcretes and the volumetric amount of coarse textured particles and fragments (> 2 mm) was taken into account. For all approaches, the RS was categorised in a 4-class system. The class of lowest RS (< 10 %) separates the very shallow sites with extremely low fine earth content. The remaining range of 10 – 100 % is subdivided into three equal-size classes of 30 %.

In summary, except for the clay & silt content and the rooting space, all parameter class limits are log-based to enable the differentiation of ecologically important changes in nutrient poor systems as well as the required wider amplitudes in highly enriched systems.

Tab. 9 gives an overview for the five selected approaches and the used parameters and classes. The analyses started with the approach 1, which uses a relatively fine-scaled classification of the parameters with 6 classes, except for the rooting space with four classes. The theoretical number of 5184 possible cases in profiles and 1,296 in topsoils is very high while in the simplest approach (5), the number of possible cases for profiles is only 432 and 108 for topsoils, respectively.

Tab. 9 Overview of the included parameters and upper class limits for the approaches 1-5. Changes compared to the previous approach are marked in italics.

approach 1

theoretical no. of cases	parameter	No. of Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
	pH	6	4,1	5,2	6,3	7,4	8,5	10,0
profile	EC	6	20	80	320	1280	5120	40000
5184	org. carbon	6	0,15	0,30	0,60	1,20	2,40	10,00
topsoil	silt & clay	6	7,5	25,0	42,5	60,0	77,5	100,0
1296	root. Space	4	10,0	40,0	70,0	100,0		

approach 2

theoretical no. of cases	Parameter	Classes	Class1	Class 2	Class 3	Class 4	Class 5	Class 6
	pH	6	4,1	5,2	6,3	7,4	8,5	10,0
profile	EC	6	20	80	320	1280	5120	40000
864	*org. carbon*	*1*	*12,0*					
topsoil	silt & clay	6	7,5	25,0	42,5	60,0	77,5	100,0
216	root. Space	4	10,0	40,0	70,0	100,0		

approach 3

theoretical no. of cases	Parameter	Classes	Class1	Class 2	Class 3	Class 4	Class 5	Class 6
	pH	6	4,1	5,2	6,3	7,4	8,5	10,0
profile	EC	6	20	80	320	1280	5120	40000
2592	*org. carbon*	*3*	*0,60*	*2,00*	*12,00*			
topsoil	silt & clay	6	7,5	25,0	42,5	60,0	77,5	100,0
648	root. Space	4	10,0	40,0	70,0	100,0		

approach 4

theoretical no. of cases	Parameter	Classes	Class1	Class 2	Class 3	Class 4
	pH	*4*	*4,0*	*6,0*	*8,0*	*10,0*
profile	*EC*	*4*	*100*	*500*	*2500*	*40000*
768	org. carbon	3	0,60	2,00	12,00	
topsoil	*silt & clay*	*4*	*7,5*	*35,0*	*70,0*	*100,0*
192	root. Space	4	10,0	40,0	70,0	100,0

approach 5

theoretical no. of cases	Parameter	Classes	Class1	Class 2	Class 3	Class 4
	pH	*3*	*5,2*	*7,4*	*10,0*	
profile	*EC*	*3*	*150*	*1280*	*40000*	
432	org. carbon	3	0,60	2,00	12,00	
topsoil	silt & clay	4	7,5	35,0	70,0	100,0
108	root. Space	4	10,0	40,0	70,0	100,0

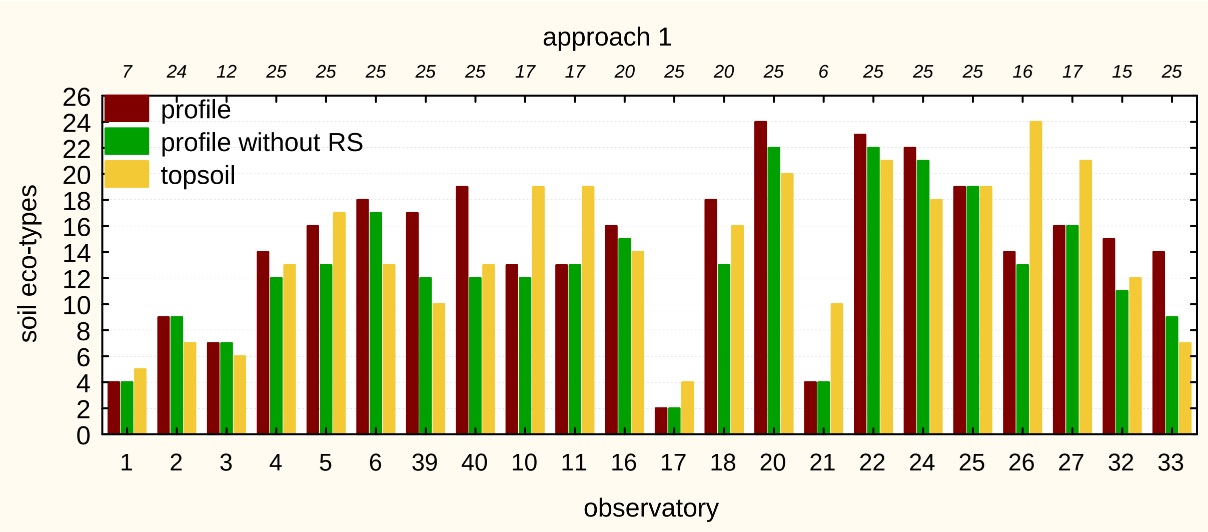
6.3.3 Results

Tab. 10 gives an overview regarding the relationships of the theoretically possible cases, the number of used profiles and the realised number of real cases in terms of applied approaches.

Tab. 10 Overview of the different approaches: TC = number of theoretical possible cases, N number of valid profiles / topsoils for analyses, FC = number of realised cases

Approach	Profile (N = 442)				Topsoil (N = 505)			
	TC	TC/N	FC	TC/FC	TC	TC/N	FC	TC/FC
1	5184	11,7	257	20,2	1296	2,6	202	6,4
2	864	2,0	169	5,1	216	0,5	91	2,4
3	2592	5,9	206	12,6	648	1,3	132	4,9
4	768	1,7	129	6,0	192	0,4	64	3,0
5	432	1,0	107	4,0	108	0,2	53	2,0

Whereas approach 1 and 3 result in quite high quotients of possible cases to realised cases (> 10), the other approaches result in lower relations with 4 to 6 “not found” cases per found case for the profiles. Topsoil variants are lower in the total number due to the lacking rooting space parameter and a higher N, but the same trend as in the profiles is evident. However, the TC/FC quotients of the approaches 1 and 3 do not differ strongly from the other approaches like the profiles do.



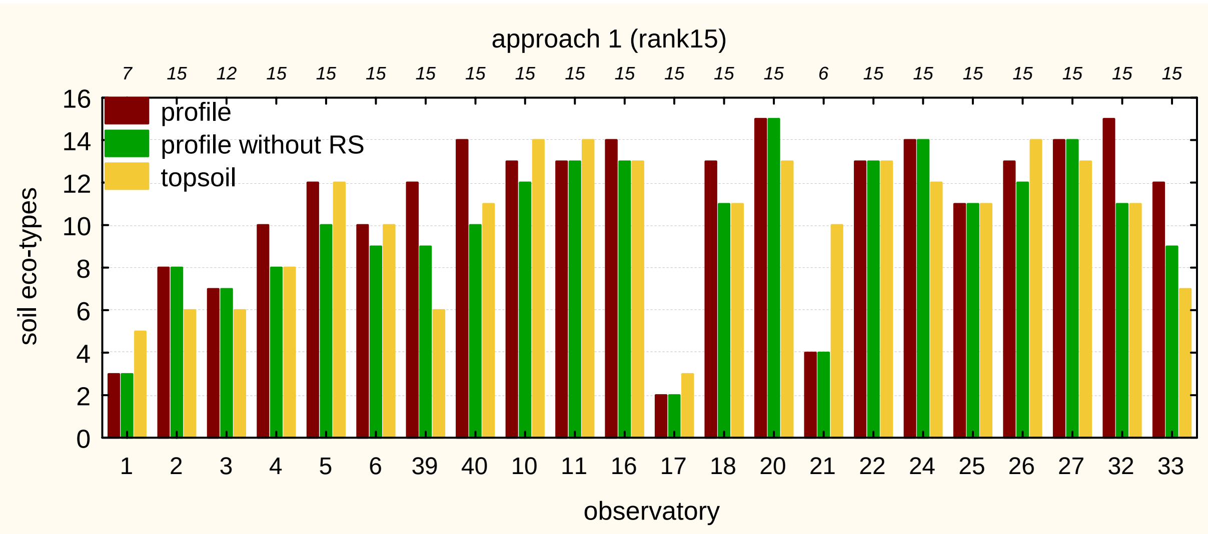


Figure 212 Number of SET per observatory using approach 1 (see Tab. 9).

Different colours indicate the data sets: profile, profile without RS and topsoil. Number on the upper x-axis indicates included locations. The lower graph includes a maximum of 15 locations per obs.

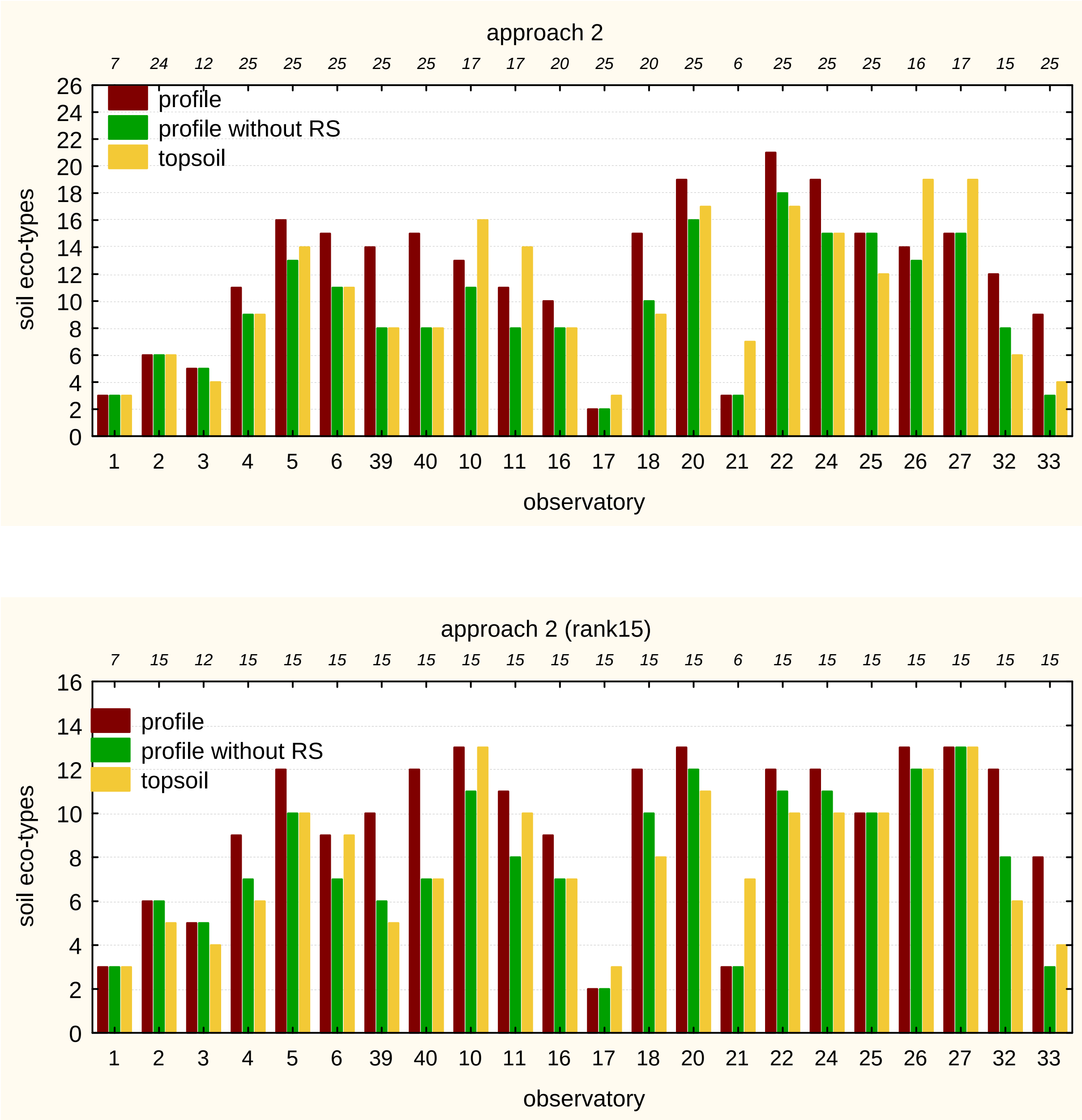
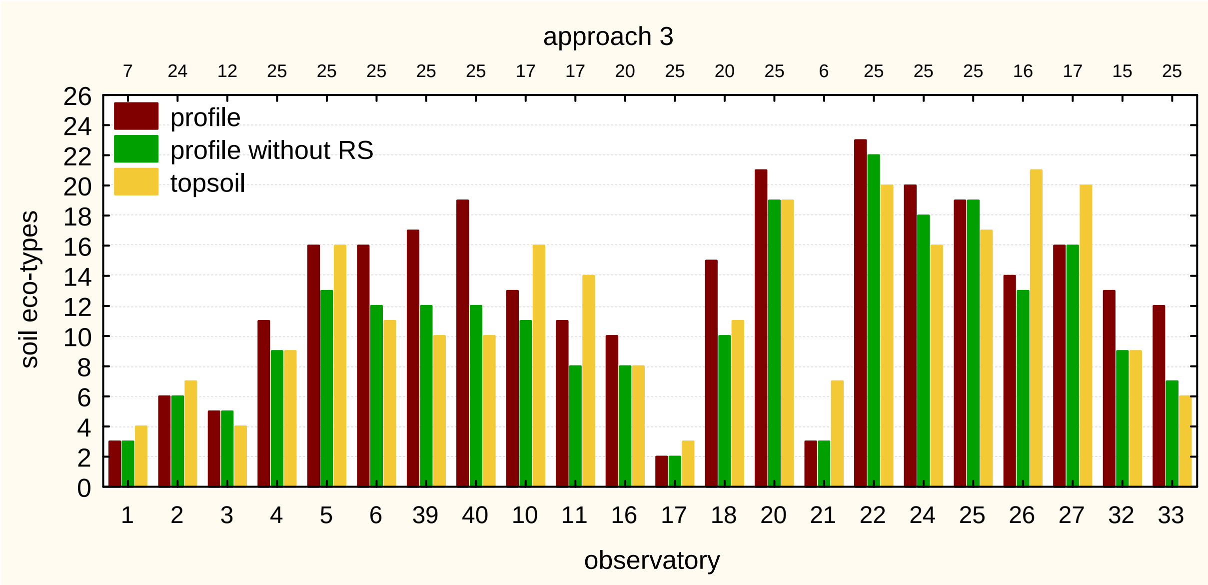


Figure 213 Number of SET per observatory using approach 2 (see Tab. 9).

Different colours indicate the data sets: profile, profile without RS and topsoil. Number on the upper x-axis indicates included locations. The lower graph includes a maximum of 15 locations per obs.



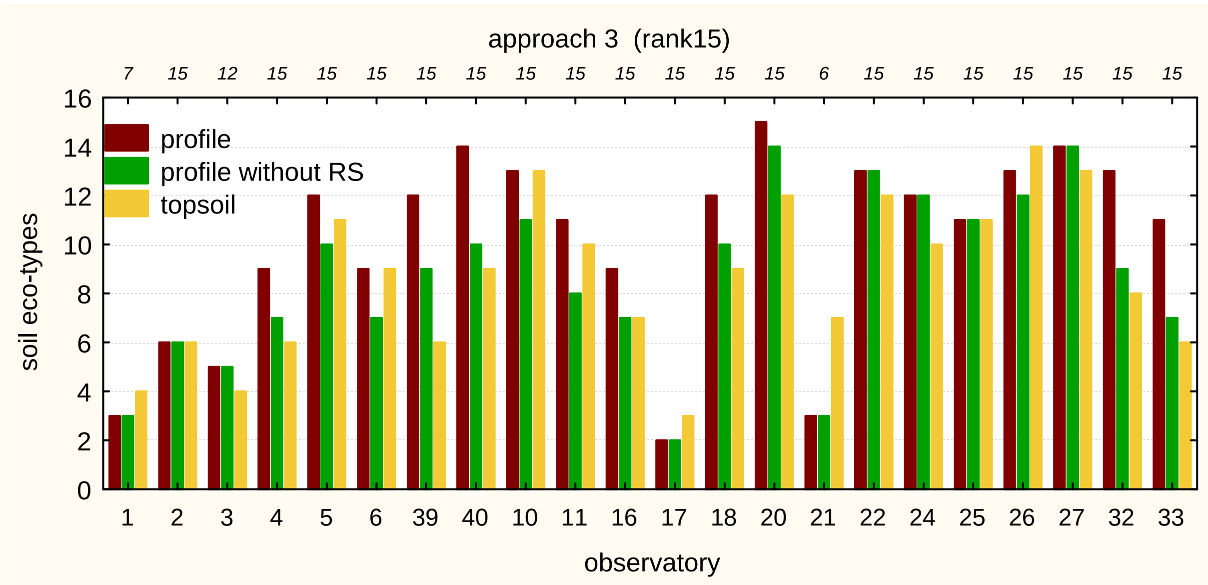


Figure 214 Number of SET per observatory using approach 3 (see Tab. 9).

Different colours indicate the data sets: profile, profile without RS and topsoil. Number on the upper x-axis indicates included locations. The lower graph includes a maximum of 15 locations per obs.

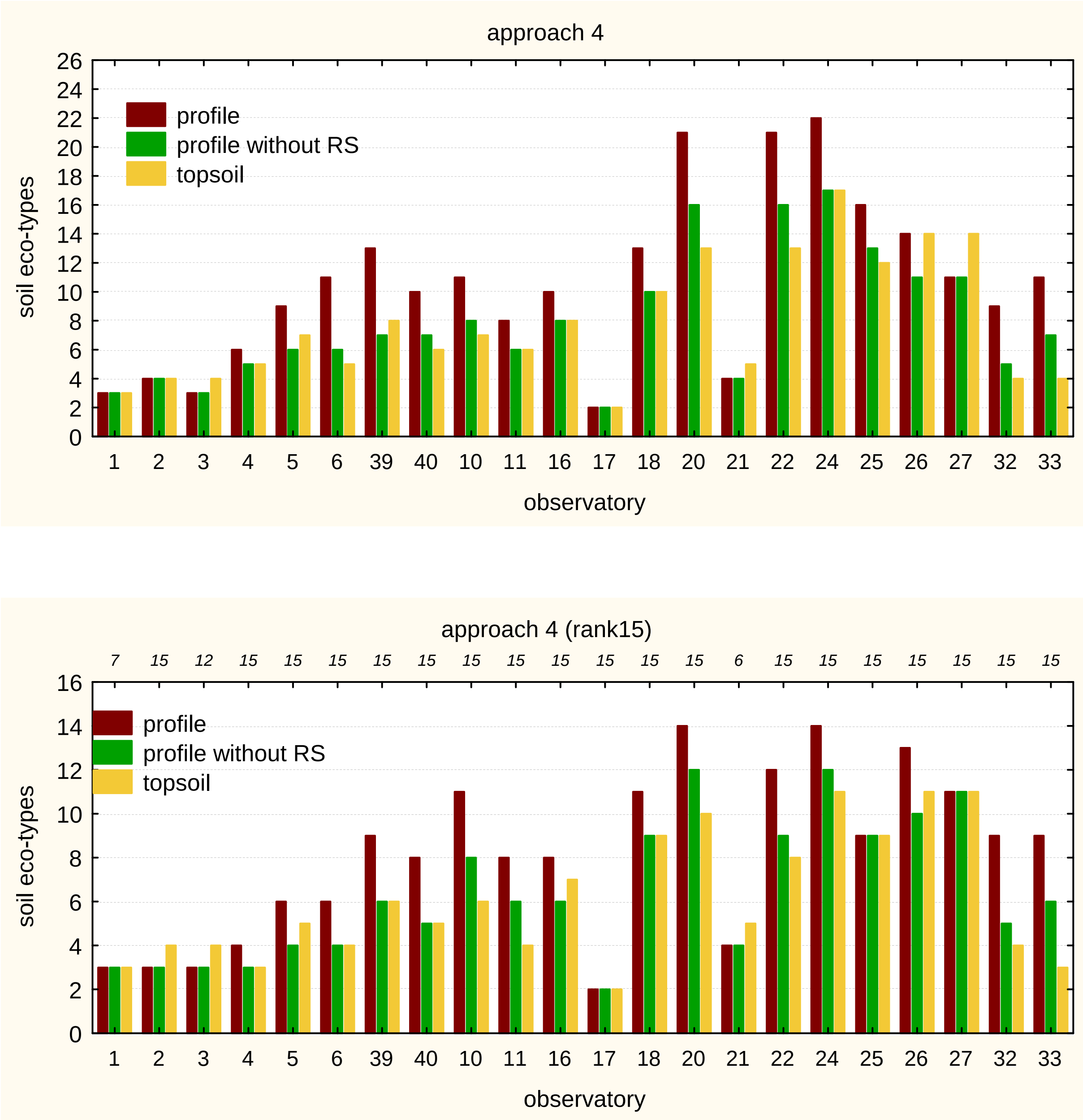
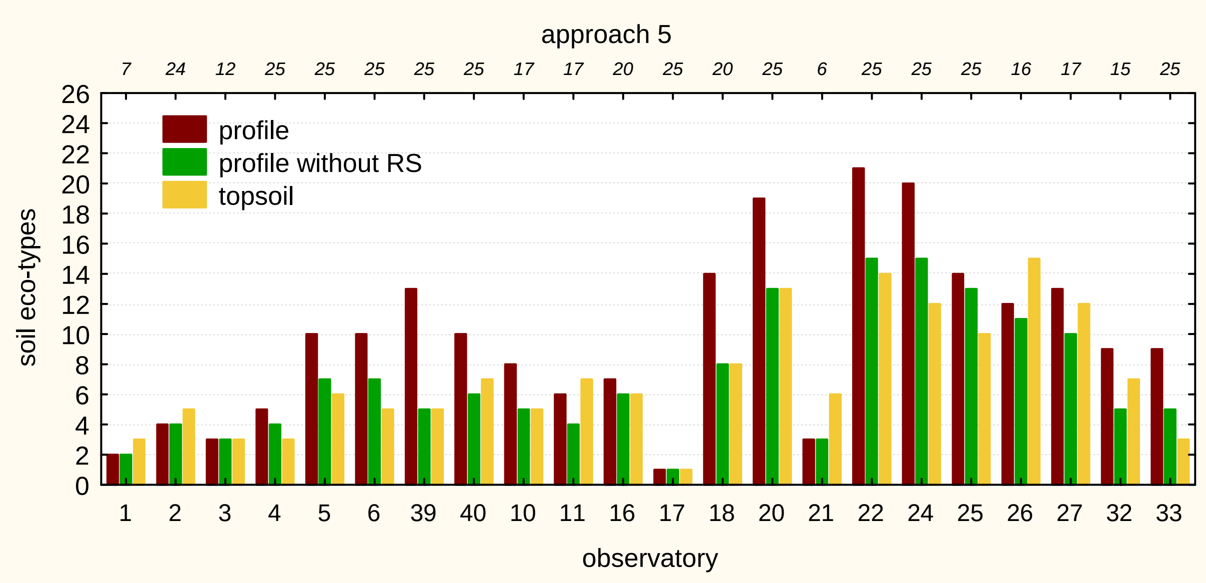


Figure 215 Number of SET per observatory using approach 4 (see Tab. 9).

Different colours indicate the data sets: profile, profile without RS and topsoil. Number on the upper x-axis indicates included locations. The lower graph includes a maximum of 15 locations per obs.



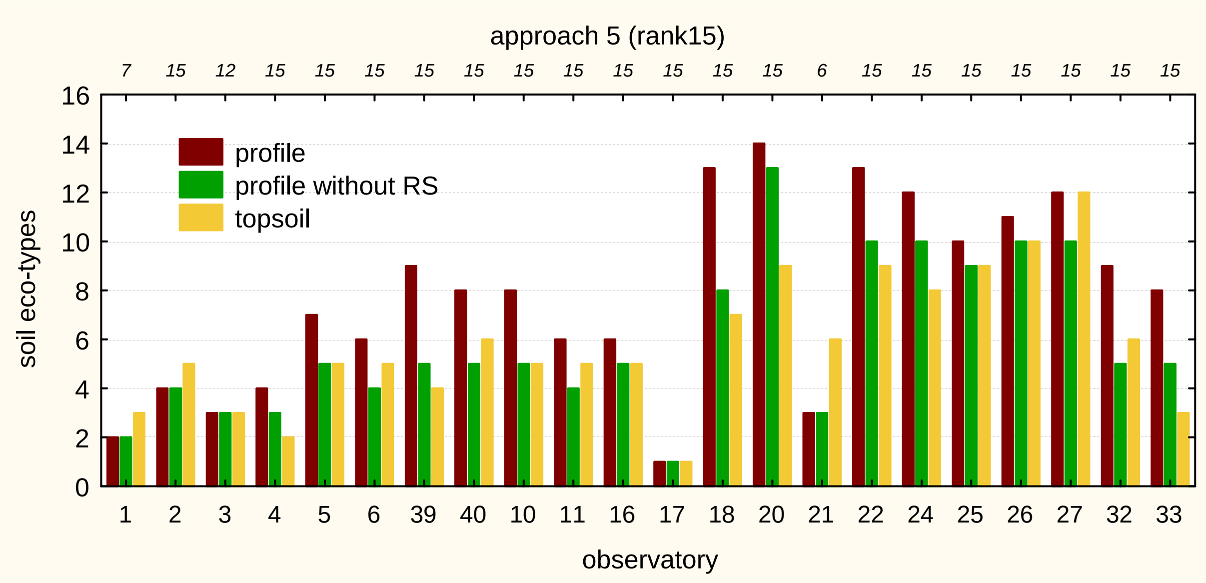


Figure 216 Number of SET per observatory using approach 5 (see Tab. 9).

Different colours indicate the data sets: profile, profile without RS and topsoil. Number on the upper x-axis indicates included locations. The lower graph includes a maximum of 15 locations per obs.

Figure 212 to Figure 216 show the number of SET, analysed with five parametric classification approaches and each divided into three variants with regard to soil data. Concerning the pedodiversity of the observatories, some general trends can be described: The lowest numbers of SET are found in the dune sand dominated observatories # 01, 02, 03, 17, 21. Within this group of observatories, the Alpha (#17) site is most homogeneous in all studied variants whereas for theYellow Dune (#21) site, the number of SET using topsoil data is for some variants larger than for single non-dune-sites. There is a clear increase of pedodiversity from the northern Kavango (#01, 02) to the less humid parts of the savanna in central Namibia. The location of the regional pedodiversity maximum differs among approaches. Using profile data including RS and regardless of the number of included profiles (15 or 25) with only one exception (approach 1), the neighbouring observatories Narais (# 39) and Duruchaus (#40) are the most diverse in the savanna region. By exclusion of the rooting depth as well as by the use of topsoil data, the centre of diversity is located at observatory #05 (Erichsvelde, approach 1 to 3) or at the observatory pair #39/40 (approach 4, 5).

Looking further to the south and west, in the drier Nama Karoo (#10, 11) and the costal desert (#16) the number of SET is decreasing compared to the maximum in those approaches that are using all available profile ($n \leq 25$) and data information (including RS). With the exclusion of rooting space, this conclusion is wrong in some approaches and by the restriction of topsoil data, in most approaches an increase in pedodiversity was calculated. Regarding the amount of available profile information, which is restricted to 17 – 20 in the observatories 10, 11 and 16, it has to be suspected that, with equal data amounts, the parametric pedodiversity of the drier part of Namibia is of equal dimension to the savanna region.

The overall pedodiversity calculated from SET is largest in the arid parts of the winter rainfall area, only for three variants the observatories #10 and #11 from the summer rainfall region are of equal size in terms of pedodiversity. The location of the maximum changes with the approaches. In most profile data cases the highest values are found on the observatories in the Richtersveld or the Namaqualand (#20, 22, and 24). In contrast, the parametric pedodiversity derived exclusively from topsoil information is largest for most approaches in the Knersvlakte (# 26, 27). For both observatories in the Cape region (# 32, 33) the pedodiversity is smaller than in the less humid regions towards the north.

By comparing the different approaches, the highest number of SET is reached with the fine scaled approaches 1, 2 and 3 as suspected. For example, with approach 1 for the observatories #20, 22, 24 and 32, the pedodiversity sums up to 22 to 24 SET from n=25 or 13 to 15 SET from n=15. This means that by applying fine scaled classification systems, almost every profile is different to the other analysed profiles. The lowest number of soil-eco-types is found on #17, the fairly homogenous dune observatory Alpha. Here the approaches result in up to four SET with fine scaled classification systems (approach 1, 25 topsoil data) and only one SET for the simplest approach 5. In general, the reduction in the resulting numbers of soil eco types by the application of more simple approaches (4, 5) is stronger in the summer rainfall area.

The comparison of the three different variants i) profile, ii) profile without rooting space, and iii) topsoil shows a trend of the highest numbers of soil eco-types in the profile variant and comparable numbers for the profile without rooting space and topsoils.

Due to the inequality of the data set when using ranking numbers up to 25, a reduction to ranking 15 was necessary to enable the best comparability. The principal trend remains stable in the reduced variant; however, few changes are evident with respect to the richness in SET. This can be shown with the example of the Koeroegabvlakte observatory (#18), approach 5. While this site is the 4th-richest observatory when using 25 ranking numbers, it upgrades to the 2nd-richest site when only using ranking 1-15. This is an effect of a relatively steep soil-eco-type area curve which decreases strongly in the higher ranking numbers above 15.

For the assessment of the five approaches, Figure 217 depicts the distribution of the SET number based on profile data including RS of observatories with an equal data basis (25 rankings: 11 observatories, 15 rankings: 19 observatories). The graphs demonstrate that for the high-class approaches (approach 1), a large number of study areas are fairly rich in SET and the variation of the central half (Box) of the areas is small. In contrast, by the reduction to 3 or 4 classes in approaches 4 and 5, the total number of SET only reduces insignificantly, but the mean of SET decreases substantially and the distribution of the central half widens.

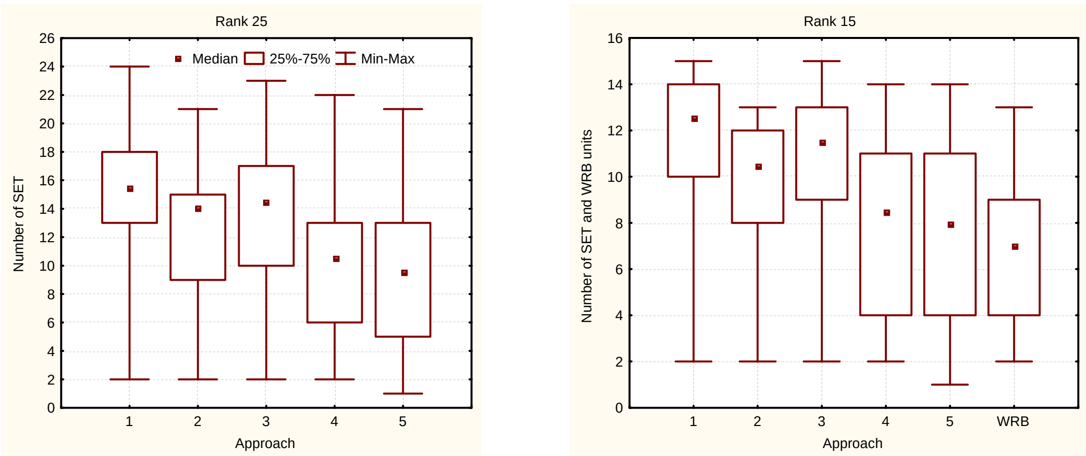


Figure 217 Distribution of the number of SET based on profile data including RS of observatories with equal data basis (left with n = 25, right with n = 15)

The parametric approach to define pedodiversity is principally undefined with respect to the amount of units. For the data set of this study, those approaches that divide the total number of SET most equally and that use the whole range of possible diversity will be regarded as optimal. The figures above demonstrate clearly that these aims are matched best by approaches 4 and 5. In comparison to the WRB (1998) system, the distribution covers a higher range and a more equal distribution of the quartiles.

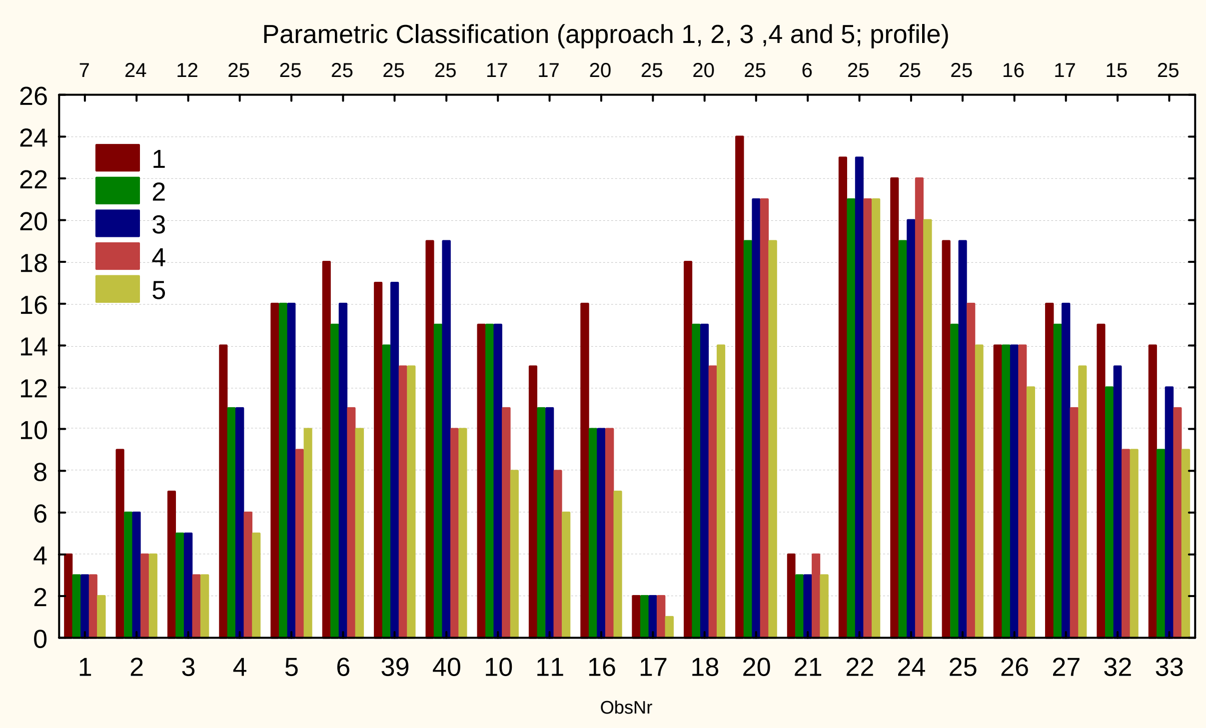


Figure 218 Summarised outcome of the five parametric classification results for profile data (x-axes = number of SET)

Figure 218 gives a summarised overview of the five different parametric classification approaches with respect to the single observatories. This is aiming at a better overview of how the different approaches affected the local or regional results. The trend of simplifying the classification from approach 1 to 5 affects all observatories in different ways with decreasing SET-numbers. The strongest reduction is observable in the approaches 4 and 5 for the observatories in the summer rainfall area (#1-17).

6.3.4 Discussion of the parametric classification approach

In comparison to the WRB classification system, the parametric classification provides a system which can be strictly focussed ecologically. The system is variable due to the selection of parameters and class sizes and therefore adjustable to various purposes. Here, the wide ranges of the parameters would already allow the application of the approach in other regions. Within the applied classification approaches 1 to 5 the system shows good sensitivity for the diversity along the studied transect with probably too detailed results in the fine-classed approach 1 and still a good stretch of the result in the approach 5.

Like in the WRB the weakness of a class-based system is the ability to produce “arbitrary diversity” if ranges of single parameters are crossing class borders though they are relatively small and would fit into one class range. One solution to overcome this problem would be the simple use of ranges with other mathematical approaches as it is described in the next chapter, which is a complete different non-class based method. Within the class-based method, one possibility is to adjust the class borders for each parameter in every single observatory but keeping the class sizes constant. By this, the real ranges would be better represented by the number of classes, but the class names and the unit qualifier are not more representative for a certain value range and therefore a comparison of soil-eco-types between observatories would be impossible. The same is true for the comparison of topsoil data with profile data, which would also have different class limits. Besides the problem of comparison, it would also be impossible to easily identify the properties of soil-eco-types such as ‘ACAB’, as the underlying values would change for every observatory and depth variant.

The parametric classification to describe pedodiversity is a new, non-established method and thus needs detailed information in case of application. It has large potential due to the openness and adaptability of the method to several research questions, but also has the disadvantage of more communication demands. However, a further field of application may be soil protection related topics, which still requires a more parametric-based, applicable methodology and transfer into procedures. This is e.g. true for the description of the ‘soil as living place for soil organisms’ as an objective of soil protection rules (BBodSchG), which lacks methods for quantification and assessment.

6.4 Pedodiversity derived from parametric space (environmental envelope)

6.4.1 Introduction

Compared to the first approach using WRB soil units, the application of a parameter-based classification as proposed with the parametric classification of the section above, presents an improvement in the reliability of the pedodiversity indices with respect to ecological meaning. However, one important deficiency in any class-based system is the fact that data variations around class limits may result in larger class numbers than for data sets with equal variation, which fit into the class limits.

Both previous pedodiversity analyses using the WRB and the parametric classification cannot exclude such variations around class borders and are therefore susceptible for some bias in terms of diversity indices. Therefore, a third approach – the parametric space -, which is able to exclude such effects, is tested here. This approach is a multivariate mathematical procedure, which is able to use the basic numerical data set and to create a unique value representing the size of ‘environmental envelope’ for each studied area. The resulting values are not numbers of species or diversity indices like calculated in the previous approaches, but n-dimensional spaces of soil properties including all cases involved. Using an equal set of parameters and keeping the normalisation of measured values constant, the procedure will provide a non-class derived measure for the comparison of different sites along the transect.

For the comparison of the explanatory power with regard to the different approaches, the selected parameters for the analyses of the parametric envelope shall be kept constant to the parametric classification approach, especially as they are defined as the most important ecological components for higher plants.

The simplest approach to quantify the parametric space is to use the ranges of each parameter and to calculate the sum of ranges as an indicator for the diversity of a certain area. Another simple approach is to define each parameter as an axis in an n-dimensional space and, by multiplying the ranges of each parameter, calculate an n-dimensional volume, i.e. the smallest rectangular limited space to enclose all data points. Because of their differing units and ranges of included parameters, both procedures are unable to use the measured values directly but need a normalisation into the same unit system of all included parameters.

A basic problem of these simple calculations is that the resulting areas and volumes may include large empty spaces and therefore overestimate the abiotic variability. This is caused by the orthogonal axis system, which implicates a total independence of the used parameters. This is rather the exception than the rule when looking at soil properties. A way to overcome this orthogonal problem is the use of the convex hull models.

The convex hull is defined for any kind of objects made up of points in a vector space, which may have any number of dimensions. The convex hull can be defined as the vertices of the smallest convex polyhedron in a space within or on which all data points lie. For a finite set of points, the convex hull is a convex polygon in two dimensions, a convex polyhedron in three dimensions, or in general a convex polytope for any number of dimensions. Figure 219 shows a simple comparison of a convex polygon, polyhedron and the related cuboid as explained above. Comparing the cuboid with the polyhedron reveals how strong the overestimation by cuboids can be.

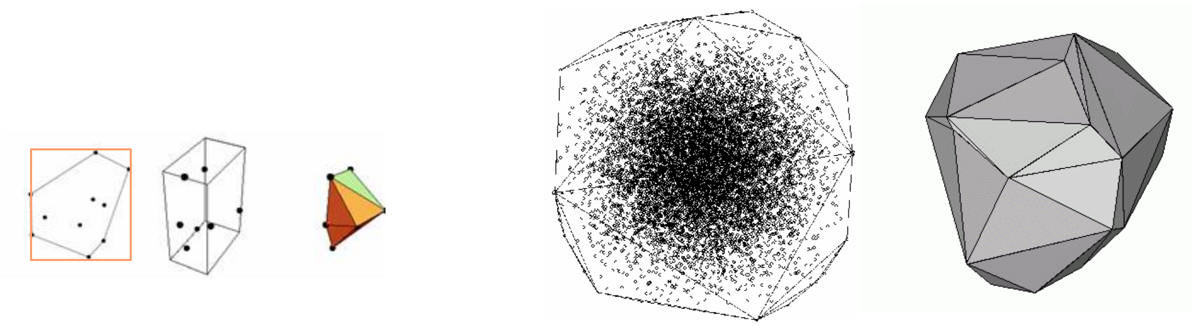


Figure 219 Examples for the convex hull principle: left) convex polygon and polyhedron with related rectangle and cuboid, centre and right) 3D illustration of convex hull

The calculation of convex hulls is a well-studied problem in computational geometry, but until now the method is rarely applied in ecology. A few studies used two-dimensional convex polygons for species range estimations based on point observation. ISLAM et al. (2005) used 2-dimensional convex polygons for correlation analyses of lab derived soil spectral signals and soil properties. In another context, CORNWELL et al. (2006) used 3-dimensional convex hull polyhedrons of plant functional traits for the detection of habitat filtering effects.

In this approach, the convex hull (and also the cuboid) shall be used to create a reliable abiotic diversity measure by using measured values of selected ecological important soil parameters. The main advantage of the convex hull method is the consideration of correlations between the used parameters. Due to the number of pre-conditions that have to be fulfilled and the quite complex interpretation of the results, it is necessary to introduce the method in detail.

6.4.2 Methods

To analyse the pedodiversity with a non-class-affected tool, a calculation of the ecological coverage of an n-dimensional space is proposed here. The general procedure of this method is, i) to select a number of ecological important soil parameters, ii) to normalise the values for each parameter and iii) to calculate the minimal space limited by a convex hull using standard software tools. A visualisation of the shape of the calculated space is only possible for two or three dimensions. Figure 206 (right column, see chapter 6.1) gives an overview of the applied method for this parametric calculation analyses. Additionally, each step is explained in the following section:

1. Selection of ecologically important parameters: this first step is analogue to the selection in the previous parametric taxonomic classification approach, this means that pH, EC, silt & clay, org. carbon and rooting space are included in the procedure. As Figure 206 explains, for the study of dimensions these parameters are combined in specific ways: For 2-dimensional analysis of convex hull: pH and EC; for 3-dimensional pH, EC and silt & clay etc.. The max. of regarded dimensions was five.

2. Normalisation / Scaling of each parameter: Before the calculation of the n-dimensional space is possible, it has to be ensured that each profile is represented with just one normalised value for all parameters involved. The normalisation into a comparable (axes-) system is important for the equality of the parameters, i.e. to prevent the dominance or underestimation of a single parameter. It is not appropriate to calculate with untransformed data, as a simple shift in measurement scale or system will change the relative weighting of a parameter. Like in the previous approach, all parameters are condensed into one single value for each profile first. This is done by a weighted average calculation for each parameter for a) topsoil (0 - 10 cm) and b) profile (0 - 60 cm). In the next step the normalisation of each parameter is done by using a scale from **0 – 1**:

$$x_i = (a_i - a_{\min}) / (a_{\max} - a_{\min})$$

with x_i = normalised value; a_i = weighted mean of original values ; a_{min} and a_{max} minimum and maximum of the entire dataset along the transect.

For EC, here a log transformation is completet beforehand in order to prevent a dominance of the high EC-values. Extreme values of organic carbon (n = 4) are reduced to 5 % C_{org} each to prevent a compression of the axis and to preserve the variability in the more important lower categories. Like in the parametric classification, the ranges are fitted to the used data set but due to the relatively wide ranges also appropriate for other regions. However, when comparing the abiotic diversity within one data set it is recommended to fit the ranges to this data set to gain the best results. For comparative analyses between different studies, it is necessary to use the same normalisation basis.

Tab. 11: Basic data for the normalisation: Extreme values of the integrated profile and topsoil values of the total data set

	Min	Max
pH [$CaCl_2$]	3.3	9.4
$EC_{2.5}$ [µS/cm]	4	28,300
Ln $EC_{2.5}$	1.4	10.25
Clay & silt [%]	0	100
C_{org}. [%]	0.10	5.0
Root. Sp. [%]	0	100

3. Combination of different dimensions: The calculations of the environmental envelopes shall be tested in different dimensions. Therefore, it is necessary to build up combinations of parameters. Here, the pH-value is used as the first dimension, the EC as the second dimension, clay & silt as the third dimension, organic carbon as the fourth dimension and the rooting space as the fifth dimension. This rank order is binding over all calculations.

4. Calculation of n-dimensional convex–hulled space: For each combination (2D – 5D) the parametric space was calculated for the topsoil (0 - 10 cm) and the profile (0 – 60 cm) data of each observatory. The calculation of the n-dimensional convex hull is a complex computational problem, which was solved by the MATLAB® Software that uses the Qhull algorithm (www.qhull.org, see also BARBER et al. (1996)). A general problem occurs in cases with no variation within at least one parameter. Here, despite potentially strong variations in other parameters, the result will be always zero. For the analysed data set, this is the case in a few areas with very homogenous sand substrates and insufficient lab analyses for clay and silt proportions. In these cases the texture was derived by the finger test and resulted for all samples in pure sand which per definition may contain a certain but small amount of clay (≤ 5 %) and silt (≤ 10 %). In this case, I decided to allow a minimum variation of 2 % in the clay & silt percentage which is comparable to other areas where texture analyses were available.

5. Handling of the results: In contrast to the previous methods, the result of each dimension calculation consists only of a single value without reference to the evenness and diversity. Thus, by calculating the n-dimensional 'environmental envelope' it is impossible to give further information on the within-space distribution of the data points. The interpretation of the parametric space should take the maximal possible volume into account. As there is usually a restricted range for each parameter of a calculated area, in comparison to the whole data set the addition of further dimensions (= parameters) to the environmental envelope reduces the calculated space. Thus, one has to be careful with comparing results of different dimensions.

6.4.3 Results

As a basic result of step 2, in Figure 220 presents the ranges of the normalised values with regard to the five selected parameters for every observatory. By this normalisation it is possible to compare the ranges for the used parameters within each observatory and along the transect. Especially in the Namaqualand region (observatory # 22 – 25), a combination of high ranges in all parameters is observable.

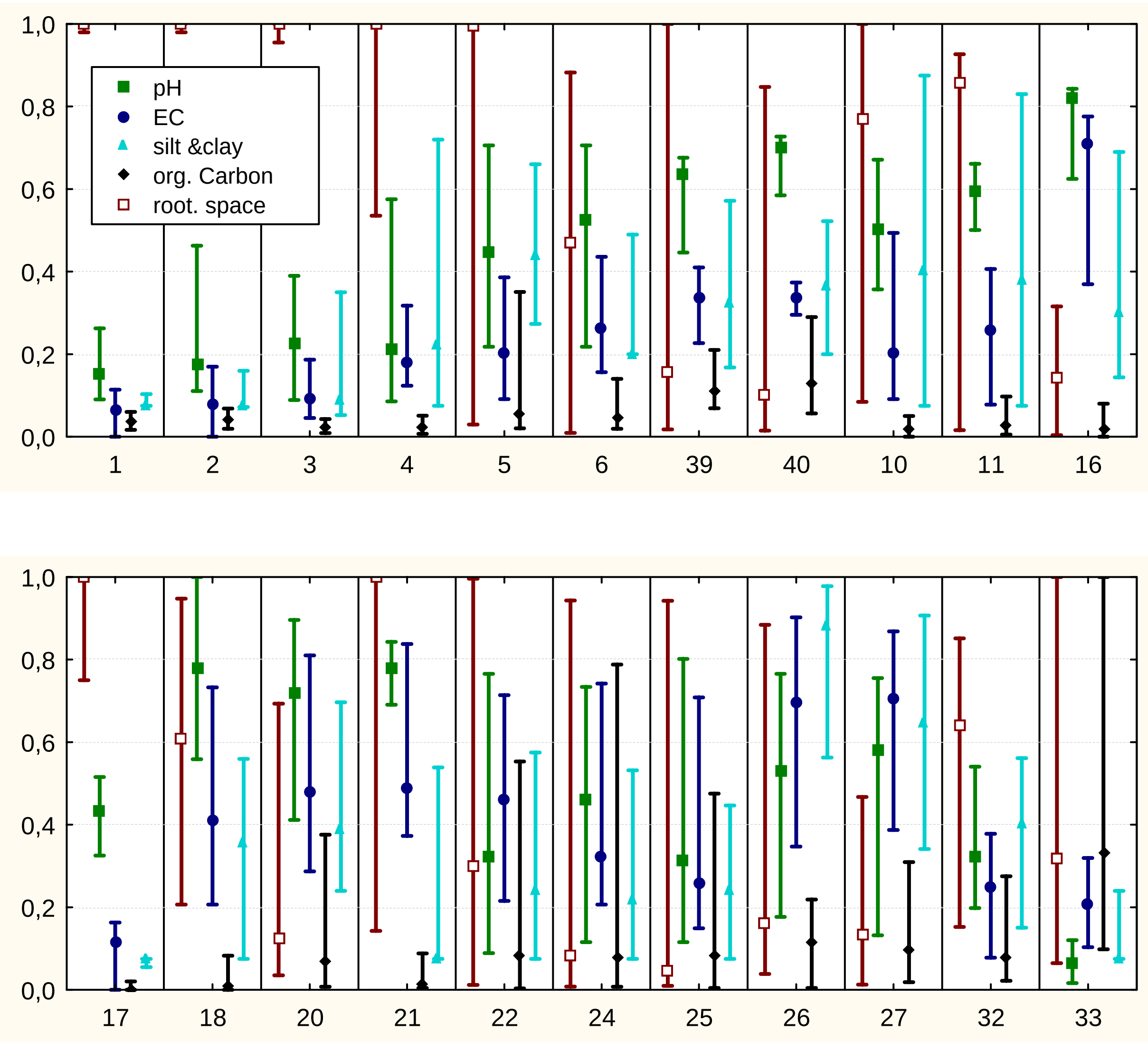


Figure 220 Ranges and median of the normalised profile values for each observatory

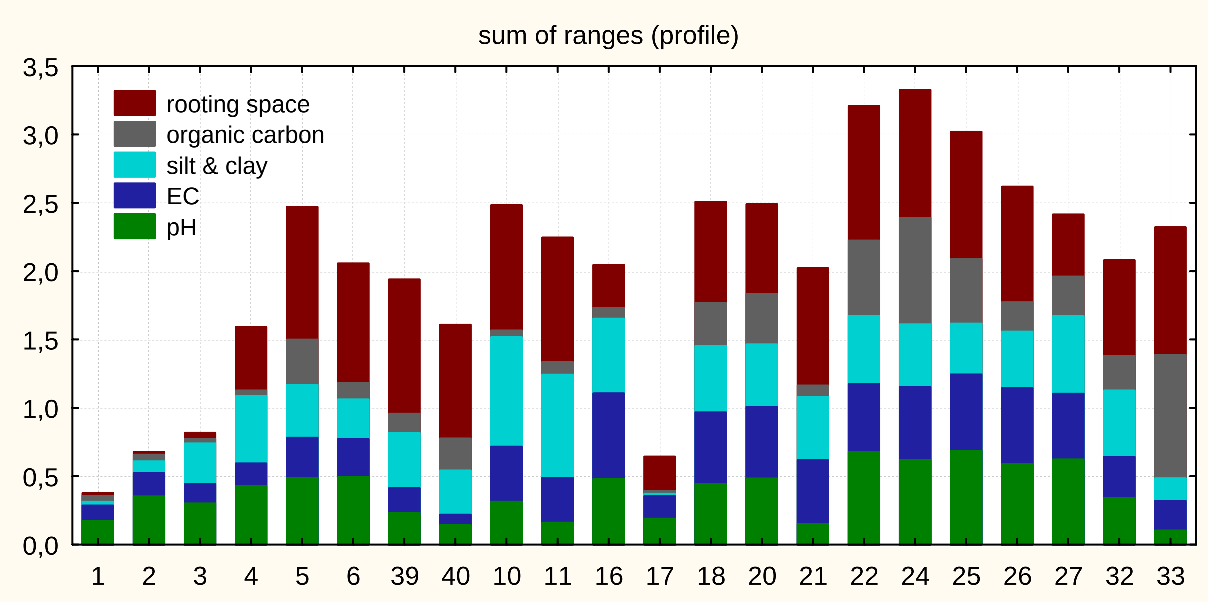


Figure 221 Stacked ranges of normalised parameter values (profile) for each observatory

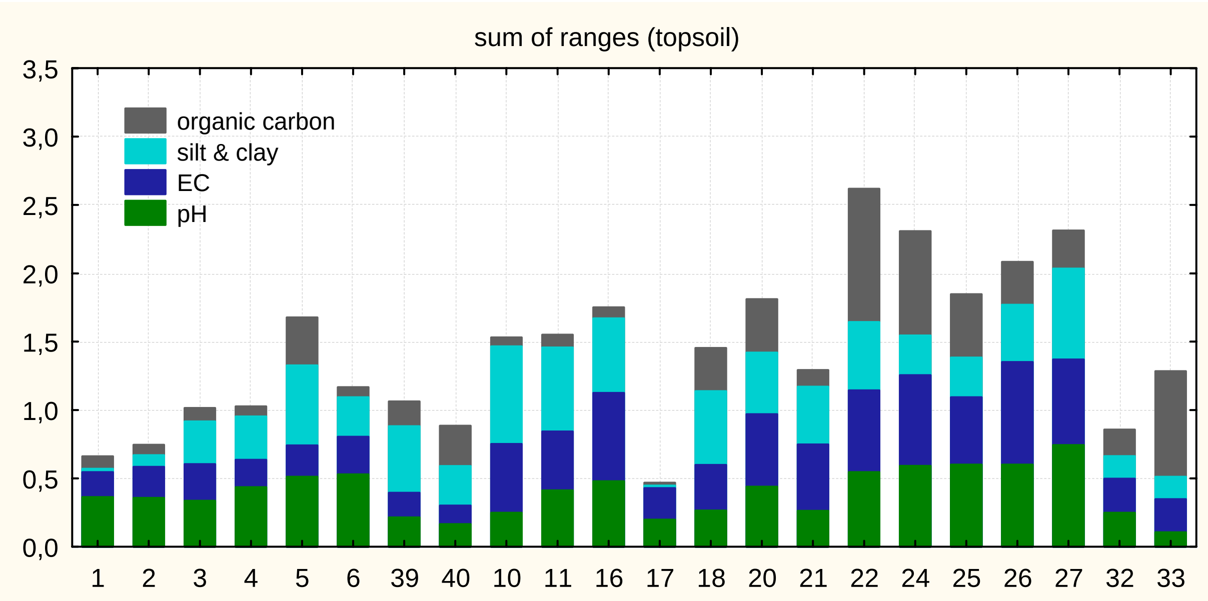


Figure 222 Stacked ranges of normalised parameter values (topsoil) for each observatory

The simplest approach for the calculation of the ecological coverage is the summarisation of the ranges as shown in Figure 221 and Figure 222 for profile and topsoil data. Lowest values are found in the dune sand dominated sites of #1, 2, 3 and 17. The dune site #21 is characterised by fairly high sums, which is an effect of a single-pan situated profile with salt accumulation and a shallow bedrock layer. The Namaqualand observatories #22, 24 and 25 reach the highest values of the whole transect. Noticeable is the higher importance of organic carbon in the winter rainfall area. Except for the dune sites, all observatories show a relatively high range of rooting space. However, comparing the median values for this parameter in Figure 220, it becomes obvious that the data distribution is very uneven. As in the example of the dune site #21, single sites often affect the ranges dominantly and therefore lead to a stronger influence of these parameters on the simple summarised ranges. In comparison to classical statistical approaches, it is not intended here to exclude such values as outliers, because they are important for the entire ecological properties of an observatory. Nevertheless, it is necessary to reduce the influence of single values as they implicate higher ranges than the normal situation in the relevant site. To minimise such effects the convex hull approach is tested.

Interpreting the results of the calculation with convex hull and cuboid algorithms requires a short introduction into the behaviour of the data in this approach. The following example introduces the behaviour of n-dimensional space. In a 2-dimensional rectangle analysis of the parameters pH and EC, with each inhabiting a normalised range of 0.5, the resulting area is 0.25. Despite the relatively high ranges of 0.5, the resulting area covers only 25 % with respect to the maximum possible result of 1. This principle continues with higher dimensions and is an inevitable mathematical law. In a 3-dimensional space with the same range of each parameter (0.5), the resulting volume reaches only 12.5 % of the maximum, in a 4-dimensional space only 6.25 % and so forth. Figure 223 illustrates this effect of bisection by adding a further dimension.

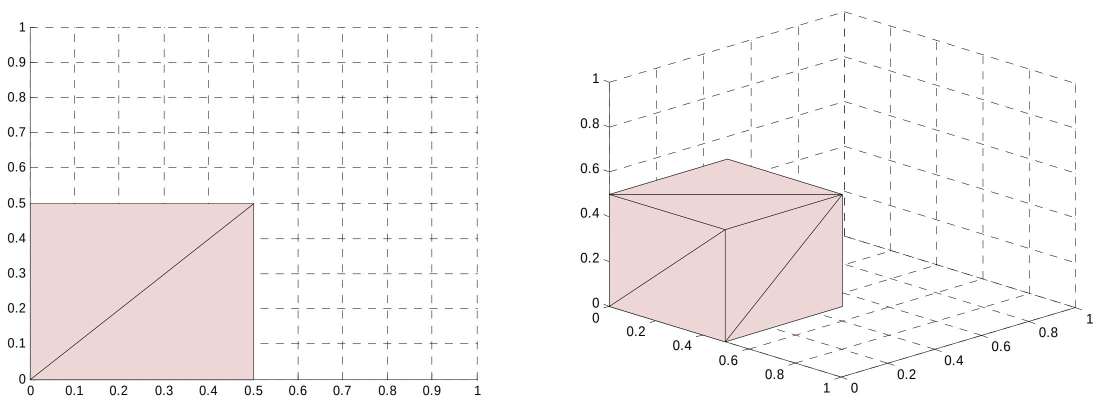


Figure 223 Illustration of the decrease effect by adding new dimension

This effect is inevitable in n-dimensional spaces. Furthermore, another normalisation procedure with integer numbers cannot prevent this. Within the used normalisation between 0 and 1, the maximum is always 1 and the compared value decreases strongly because of the numbers below one. A normalisation between 0 and 100 would cause an increase of the resulting values when adding a dimension, but the maximum would also increase strongly. The relationship would be the same as in the 0-1 normalisation data.

Figure 224 shows an example of the results of the convex hull analyses in 2D and 3D for the observatories #17 Alpha and #22 Soebatsfontein. Here, the main advantage of the convex hull principle, the consideration of correlation effects, is demonstrated. In the 2D example of Alpha, the relatively small convex area is a result of both, the small ranges of EC and pH-value and high correlation of these parameters. In the example of #22 Soebatsfontein higher ranges and a lower degree of dependence of the parameters cause larger convex hulls which result in higher values for the convex polygon and polyhedron, respectively. For the comparison, the rectangles resulting from the simple ranges are shown as a dotted line. In the case of #17, the overestimation of the environmental envelope would be around 100 % with the rectangle method. This effect of 'empty spaces', which is a problem of rectangles and cuboids, is less evident, but also present when looking at the data distribution of in the example of #22 Soebatsfontein. Here, in the convex approach empty spaces predominantly occur between data points and to a lesser extent outside the distribution of the data cloud. As the soil is regarded as a continuum with transition states, it can be assumed that these empty spaces are covered by non-surveyed sites, at least as small border regions. Thus, the incorporation of such areas in the calculation is required.

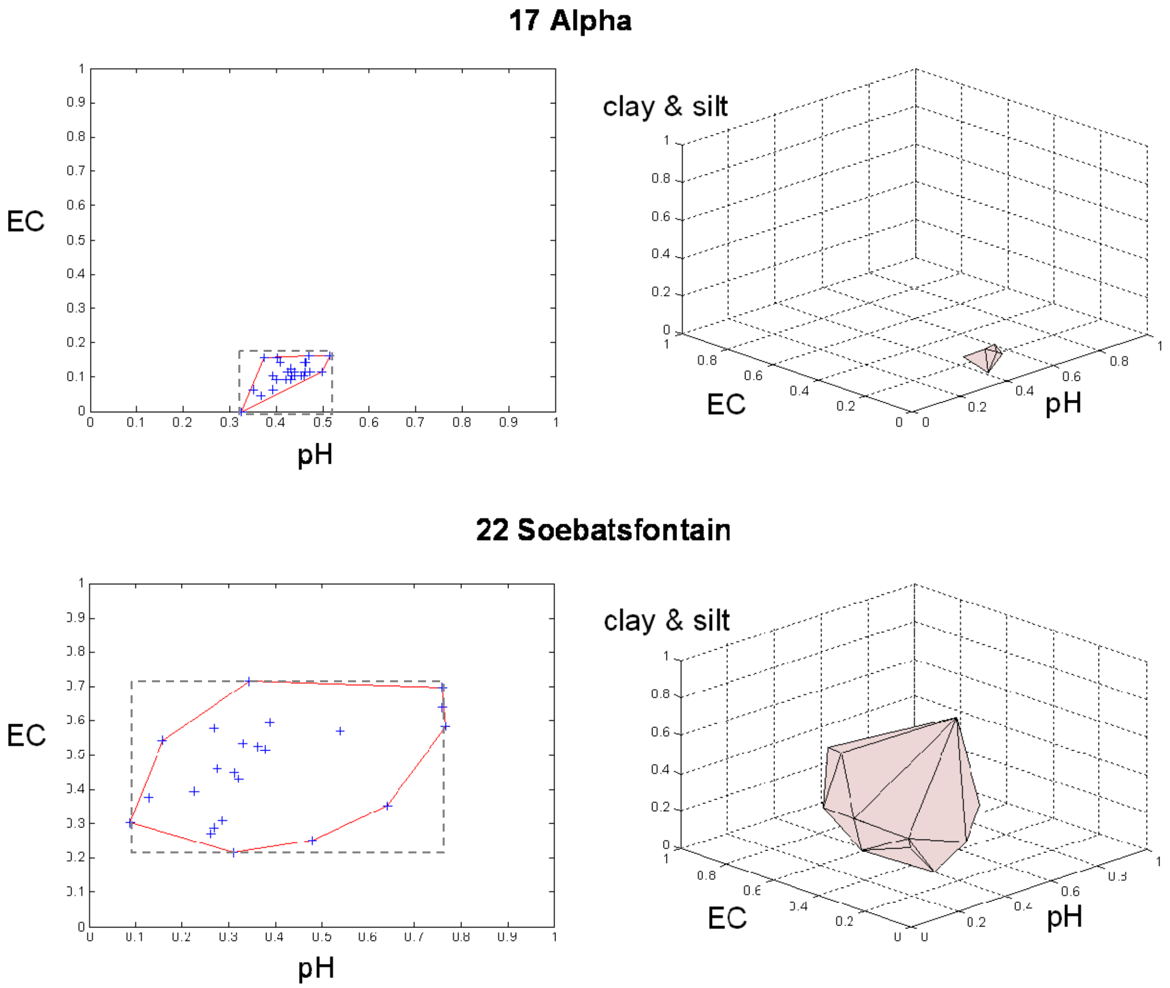


Figure 224 Example of the results of the convex hull analyses in 2D and 3D for the observatories #17 Alpha and #22 Soebatsfontein

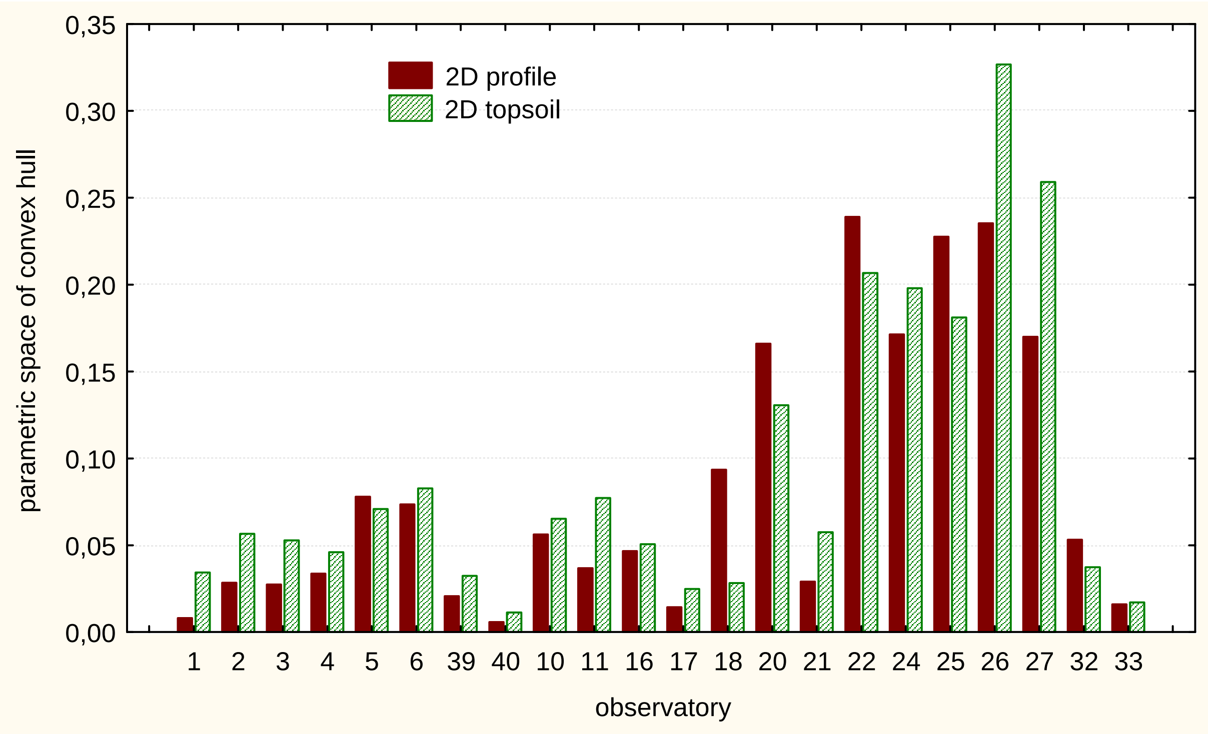


Figure 225	Parametric space of 2D convex hulls for profile and topsoil

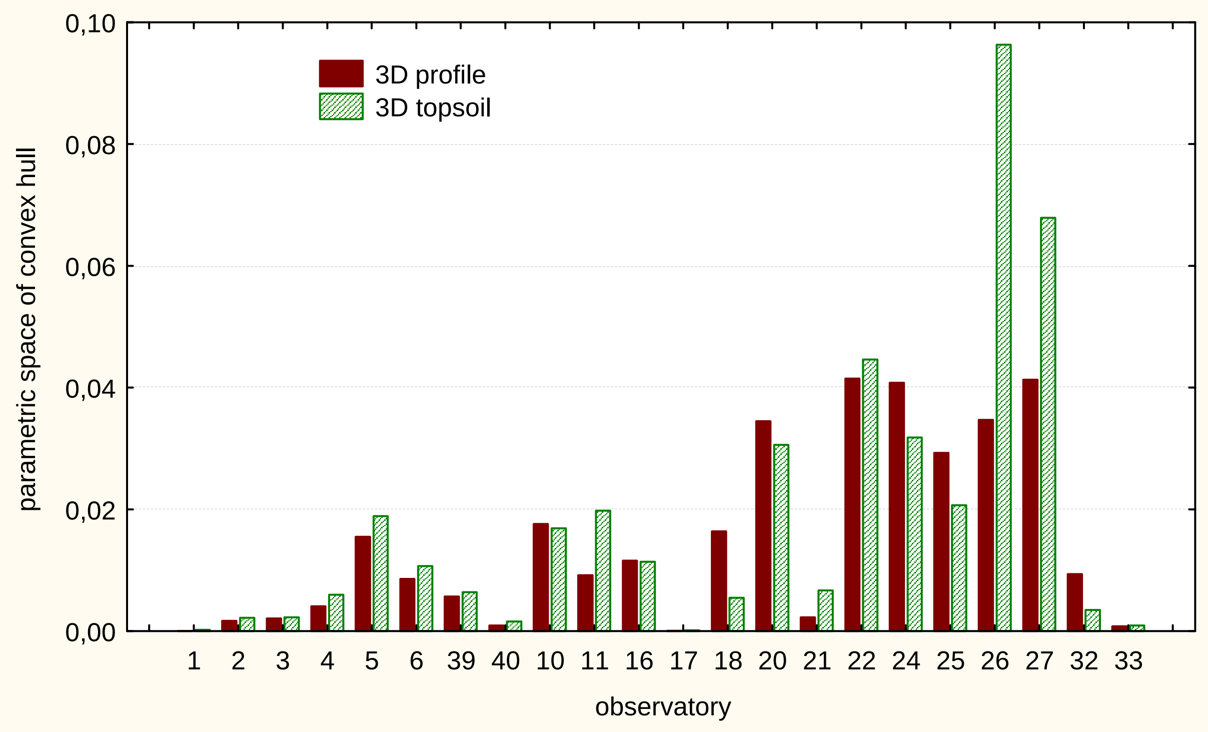


Figure 226	Parametric space of 3D convex hulls for profile and topsoil

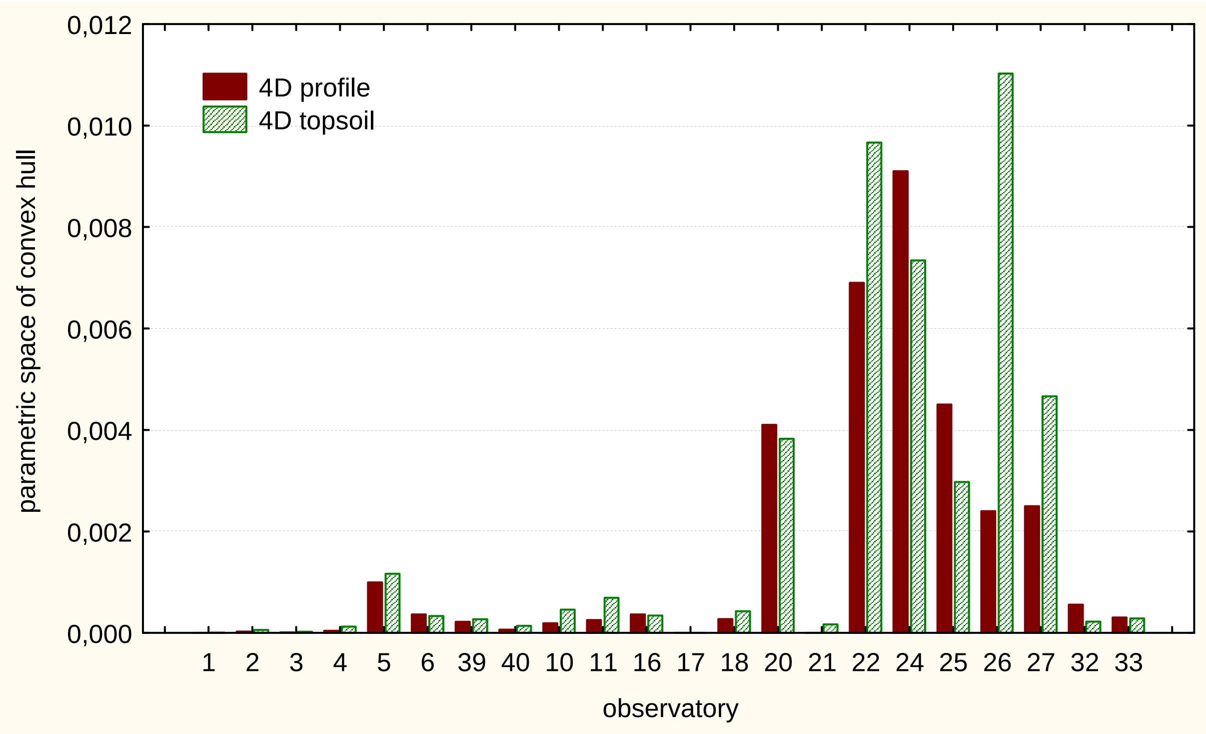


Figure 227 Parametric space of 4D convex hulls for profile and topsoil

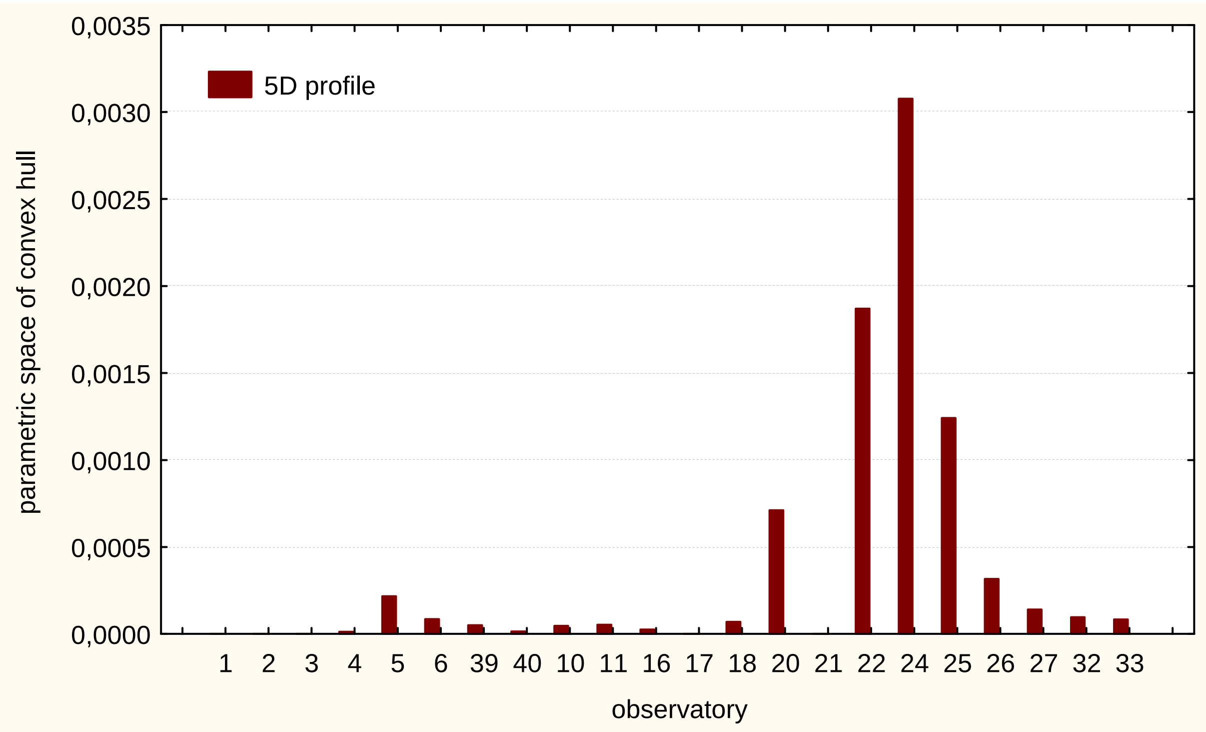


Figure 228 Parametric space of 5D convex hulls for profile

Figure 225 and Figure 226 show the results of the convex hulled space calculation for 2D and 3D along the transect. Like in the previous parametric taxonomic classification approach, values were calculated separately for the profile and the topsoil data. The theoretical upper limit of each calculation is 1, which would mean a range of 1 for each parameter and a strictly orthogonal or non-correlated relationship between the parameters. The above-described effect of significant reduction in terms of resulting values with higher dimensions is already detectable at the chosen scales in the graphs. It is important to notice that the different dimensions are not comparable with respect to their calculated values. Whereas the 2D approach reaches maximum values of 0.33, which means a coverage of 33 % of the maximum possible area, the fifth dimension only reaches 0.003 (0.3 %) as a maximum value. This underlines the incomparability of the space-values from different dimensions (see also explanation in methods above).

Another problem in the higher dimensions (3D-5D) is the unequal stretching of the ranges in the results. Whereas in the 2D approach differences between single observatories can be shown on the same scale, the relative distance between the results in the higher dimensions increases strongly. This also leads to difficulties with the graphical presentation of the results. One way to solve this problem is the use of a log scale in higher dimensions, which enables a better ranking of the results. Here, a linear scale for all graphs is used to allow a better interpretation and comparison of the different dimensions approaches.

The basic trend in all used dimensions (2-5) can be described as follows: starting with low values in the northern Kavango (#1-3), continued with increasing values in the central savanna sites (# 4,5,6,). The Rehoboth savanna (#39, #40) shows very low values whereas the Nama Karoo sites (#10,11) and the coastal desert of the Namib (#16) are comparable to the central savannah. The Kalahari site Alpha (#17) and the coastal dune site of Yellow Dune (#21) show low values. With the start of the winter rainfall system in the Richtersveld (#18, 20) a strong increase in the values can be observed in the Namaqualand (#22, 24, 25) which is continued to the Knersvlakte (#26, 27). The Cape region (#32, 33) again decreases with medium to low values.

The relationship between the parametric spaces of the topsoil and the profile data sets is not constant but of comparable dimensions. There is a slight trend to higher topsoil values in the summer rainfall region and higher profile values in the winter rainfall region, except for the sites in the Knersvlakte (#26, 27). Here the topsoil values significantly override the profiles. This is caused by the special situation of salt and silt accumulation in the topsoil of several profiles. In the other cases, the accumulation of salts in deeper soil horizons and the high variability of soil depth and coarse fragments are more dominant than in the summer rainfall area and therefore lead to higher profile values. Whereas the rooting space variability is an effect of the mountainous and bedrock influenced observatory selection, the non-salty subsoils in the summer rainfall area are a result of stronger leaching and drainage of soils due to higher precipitation amounts and intensities.

Besides the mentioned space reduction effects of increasing dimensions, a number of differences in the results of the different approaches are evident. Whereas the 2D and 3D profile approaches provide comparable values for the entire Namaqualand, the 4D and 5D values for the Knersvlakte decrease significantly. This is an effect of the parameters organic carbon (4D) and rooting space (5D), which have a stronger impact on the other Namaqualand sites. Although ranges for these parameters are also high for the Knersvlakte (see Figure 220), they are stronger correlated with the other parameters in the profiles. Figure 229 and Figure 230 describe these effects of a possible increase by adding the next dimension or parameter. Besides the description of ranges, like in Figure 220, this graph shows the importance of each parameter for the convex hull results by inclusion of correlated effects. Each observatory is represented by four different colours; each colour stands for a parameter or a new dimension, respectively. The range of each colour gives the percentage of the maximal possible increase when adding this dimension or parameter. E.g. an increase of 100 % in EC would require the maximum range of 1 as well as orthogonal properties for each point of the convex hull. It has to be noted that the resulting range in the graph is not a measure for the volume of the convex hull and always a result of the combination of orthogonality and the range of the parameter. It is also important to note, that the relative increase would show different results by changing the ranking of parameters included. Nevertheless, the graphs provide valuable information about the dominance of the different parameters in the single observatories. This principle could also be applied for the analysis of parameter strength in a single observatory when ranges are adapted to this reduced dataset.

The above-mentioned case of reduced values in the fourth and fifth dimension for the observatories #26 and #27 is shown in Figure 229 in terms of the lower importance of the parameters organic carbon and rooting space in comparison to the observatories #22-25.

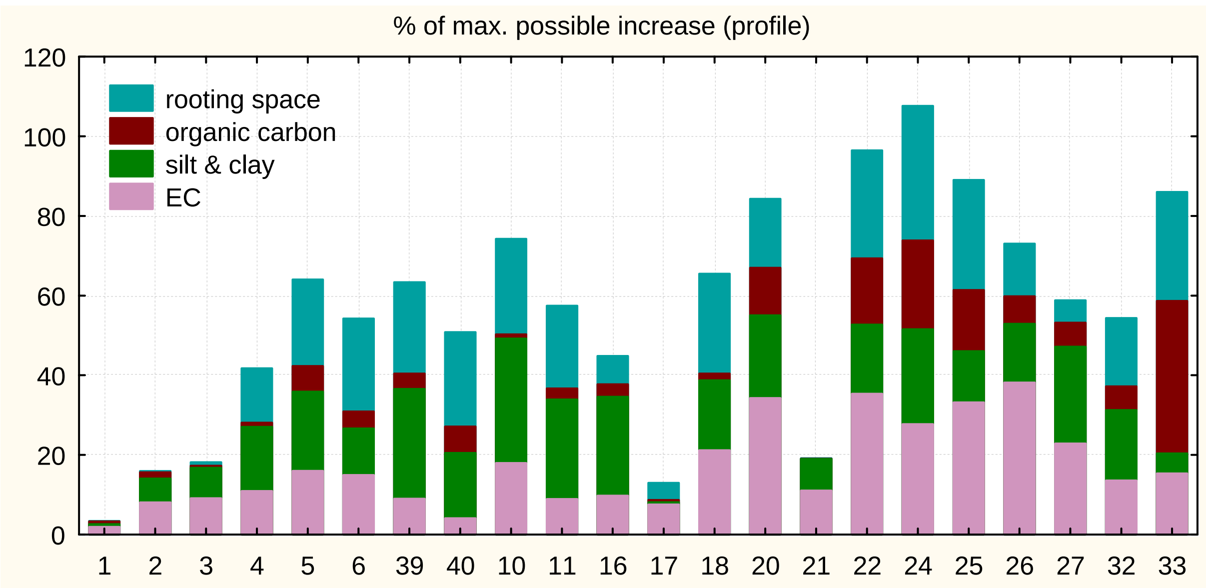


Figure 229 Illustration of the percentage of max. possible increase based on 1D (pH) over 2D (ph & EC) to 5D (increase by RS) for profile values

Another example for the correlation strength within the set of parameters is the comparison of the observatories #18 and #20 which have identical ranges for each parameter (see Figure 220) but strong differences in the resulting convex areas and volumes (Figure 225 and following). The underlying correlation effects are higher in the observatory #18, which is demonstrated by a lower proportional increase of each parameter in Figure 229.

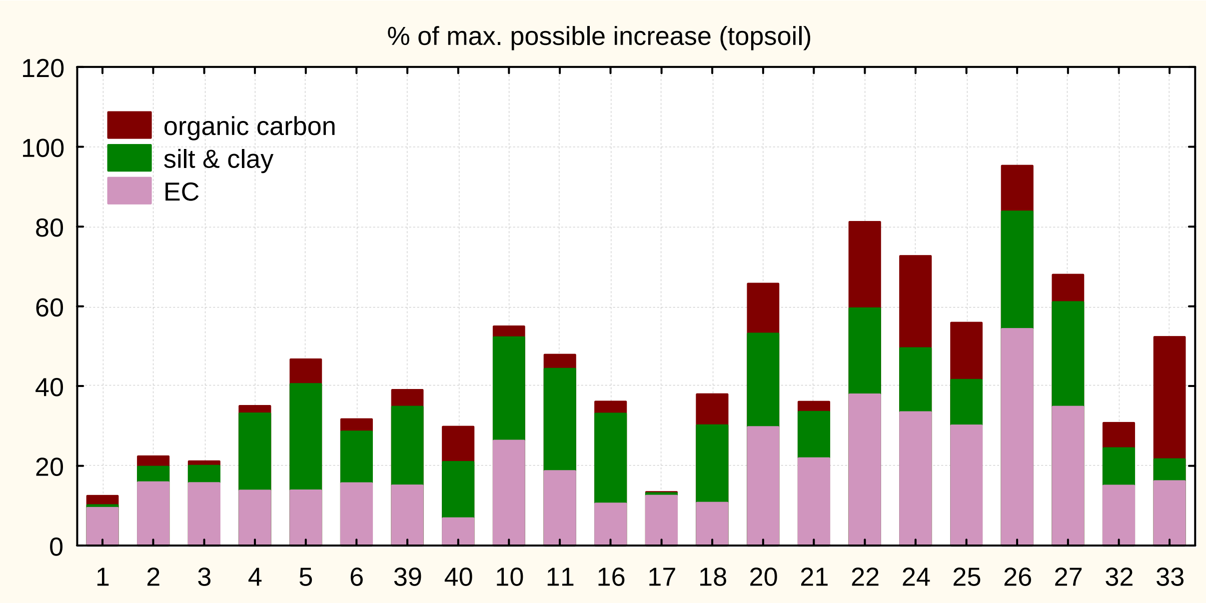


Figure 230 Illustration of the percentage of max. possible increase based on 1D (pH) over 2D (ph & EC) to 4D (increase by organic carbon) for topsoil values

6.4.4 Discussion of parametric space approach

This third approach aimed at a better estimation of the real ecological coverage by means of calculating the parametric space using the convex hull algorithm. The most important advantage of the parameter-based calculation methods vis-à-vis the classification approaches is the insensitivity against the position of class borders. By the use of measured unclassified data, the total information within the data set is involved and no arbitrary loss or overestimation of pedodiversity can occur.

An important disadvantage of the multidimensional convex hull and orthogonal system calculations are that they are difficult to communicate and that they are rather sensitive to small ranges of parameters. All methods aiming at a calculation of areas or volumes by using the ranges of parameters have the problem that a small range in one single parameter can minimise the result independently from the other parameters included. This is for instant the case in the observatories with almost pure sand where the silt & clay parameter has very small ranges. The results are minimised by adding the third dimension (silt & clay) and cannot increase significantly in the fourth and fifth dimension. Therefore, it is necessary to have the additional information about the proportional increase when adding a new dimension to identify the strength of the different parameters (see Figure 229 and Figure 230). The simple summarisation of ranges does not have this problem but is not sensitive to the distribution of the data, i.e. the correlation between the parameters. To avoid these problems, the exclusion of invariant parameters is possible. This may for instance be done for all dune sites to compare their within-group pedodiversity. But with the objective of this study to compare the diversity of sites with rather different pedological settings with a sound procedure, the change of included parameters along the transect is not appropriate.

Taxonomic approaches are also suitable to include correlation effects by naming the objects. However, variability in one single parameter can thus produce high numbers of soil-eco-types independently from the highly correlated other parameters. In the ecological coverage approaches, these effects are not possible. Another advantage of the ecological coverage is the inclusion of space between data points which can be regarded as “ecotones” in the soil continuum.

I interpret the convex hull volume as an advantage over rectangular methods in that the convex hull quantifies parametric areas and volumes more precisely by excluding the missing corners of a triangular data distribution. This method is basically a step back into the functional continua paradigm and therefore “closer” to the reality than the discrete groups approaches. However, it requires more “translational” work as it is a new and non-established method.

6.5 Topodiversity of the observatories

Tab. 12 and Tab. 13 show the results for the topodiversity analyses on the observatories. It is important to notice that the majority of the observatories were selected in plain areas, i.e. the variance in topography is not representative for the region. Although topodiversity is assumed as one major factor influencing biodiversity on the regional scale, the aplied scale of this study (1 km^2) is not appropriate to concentrate solely on topodiversity. Nevertheless, with respect to some differences between the observatories the data is presented here.

Tab. 12 Topodiversity along the transect by statistical values of the entire observatory

Nr.	Name	Height absolut (m)					
		Min.	**Mean**	**Median**	**St.-dev.**	**Max.**	**Range**
1	Mile 46	1178.4	1181.7	1180.6	2.9	1194.1	15.7
2	Mutompo	1176.8	1181.7	1180.6	3.2	1192.1	15.3
3	Sonop	1220.9	1226.7	1223.5	5.7	1239.0	18.1
4	Omatako	1517.3	1521.9	1522.2	1.9	1525.1	7.8
5	Otjiamongombe	1492.9	1496.9	1496.8	1.7	1500.7	7.8
6	Okamboro	1486.1	1497.9	1498.1	4.4	1508.5	22.3
10	Gellap Ost	1097.2	1119.4	1118.6	14.5	1163.7	**66.5**
11	Nabaos	1044.8	1074.7	1073.5	14.8	1105.5	**60.7**
16	Wlotzkasbaken	64.4	74.8	74.8	4.6	83.0	18.6
17	Alpha	893.4	897.1	896.6	2.4	904.2	10.8
18	Koeroegapvlakte	608.1	637.4	635.7	14.2	674.3	**66.3**
20	Numees	346.7	389.9	377.1	40.8	551.7	**205.1**
21	Grootderm	191.0	206.5	204.9	9.0	227.5	36.4
22	Soebatsfontein	263.0	327.8	322.0	41.7	434.4	**171.4**
24	Leliefontein	1019.7	1059.2	1055.7	29.1	1132.8	**113.1**
25	Remhoogte	1009.5	1036.0	1032.8	15.5	1076.5	**66.9**
26	Flaminkvlakte	213.5	232.5	231.8	9.9	253.6	40.1
27	Ratelgat	212.2	230.0	230.5	8.5	245.8	33.6
32	Elandsberg	95.2	99.9	99.8	2.3	105.1	10.0
33	Cape of Good Hope	63.9	98.8	100.4	8.6	113.8	49.9

Included data consist of 121 DGPS measured heights on each observatory (100 m grid). Whereas the first table shows the height in m asl and the total range in height within the observatory, the second table focuses on height changes across a distance of 100 m. The mountainous sites #20, 22, 24 show the highest total ranges followed by #10, 11, 18 and 25. However, the case of #18 shows that it is important to also focus on the smaller distances as a measure for topodiversity. The observatory #18 is located in the Koeroegabvlakte, a basin / glacis structure with 66.3 m total height difference comparable to the observatory #10, but dominated by a smooth inclinated plain resulting in comparably low short distance differences of maximal 7.3 m. Another example is the observatory #17 Alpha. This site is characterised by small linear dunes and has a very low range in absolute height asl but a comparable high mean height difference on the 100 m distance. The observatories #05 and #32 show the lowest topodiversity values.

Tab. 13 Topodiversity along the transect by statistical values of the 100 m distances in the obs.

Nr.	Name	Height difference 100 m distance (m)					
		Min.	**Mean**	**Median**	**St.-dev.**	**Max.**	**Range**
1	Mile 46	0.0	1.8	0.9	2.2	13.5	13.5
2	Mutompo	0.0	2.1	1.0	2.5	12.5	12.5
3	Sonop	0.0	1.2	0.8	1.2	5.4	5.4
4	Omatako	0.0	0.8	0.6	0.6	3.2	3.2
5	Otjiamongombe	0.0	0.6	0.5	0.6	3.3	3.3
6	Okamboro	0.0	1.8	1.6	1.3	6.2	6.2
10	Gellap Ost	0.0	3.5	2.9	3.7	24.8	24.8
11	Nabaos	0.0	3.3	3.1	1.9	16.3	16.3
16	Wlotzkasbaken	0.0	1.5	1.2	1.2	6.6	6.6
17	Alpha	0.1	2.7	2.3	2.0	9.0	8.9
18	Koeroegapvlakte	0.3	3.1	3.0	1.5	7.3	7.0
20	Numees	0.1	13.2	7.1	15.4	79.9	79.8
21	Grootderm	0.0	2.3	2.2	1.5	7.1	7.1
22	Soebatsfontein	0.1	10.0	8.3	7.5	35.5	35.4
24	Leliefontein	0.1	7.4	6.3	5.2	27.2	27.1
25	Remhoogte	0.1	5.6	5.1	3.4	16.5	16.4
26	Flaminkvlakte	0.0	4.7	4.4	3.2	16.8	16.8
27	Ratelgat	0.0	3.5	3.0	2.9	17.5	17.5
32	Elandsberg	0.0	0.6	0.5	0.5	2.3	2.3
33	Cape of Good Hope	0.1	3.6	2.6	3.9	28.6	28.5

6.6 Soil inventory area curves

Species area curves are a common tool in ecology for the analyses of the spatial or sample behaviour of richness patterns in plant or animal communities (ROSENZWEIG 1995). Sample series along a transect, random plots, or a continuously increasing sampling area are used for the construction of species area curves. These curves provide useful information on habitat borders, patch sizes and regional trends of species distribution. Estimating species richness for the entire assemblage from individual samples can be obtained by extrapolating species area curves.

The tool is used here to show the behaviour of the soil inventory of an observatory by summarising the found soil units with increasing ranking numbers. Although reflecting point-related pedon information, here the ranking numbers are regarded as the spatial context. Compared to size-increasing Whittaker plots used in phytodiversity studies, here a higher sampling intensity within defined areas is used as the spatial increase. With regard to the methodology of applied ranking procedure it is important to note that the habitat classification and the resulting ranking list strongly influence the pattern of these curves, i.e. creates steeper slopes with fewer samplings. Comparative analyses should therefore include the same ranking procedure.

The behaviour of the different sites with respect to the soil inventory using the WRB (FAO 1998) is shown in chapter 6.2.3 and has revealed that various curve behaviours indicating a range from complete capture of the soil inventory to few sites with a strong increase in high ranking numbers. The latter are an indication of the fact that despite the high survey intensity of 25 profiles per square kilometre, the soil variability is not captured totally..

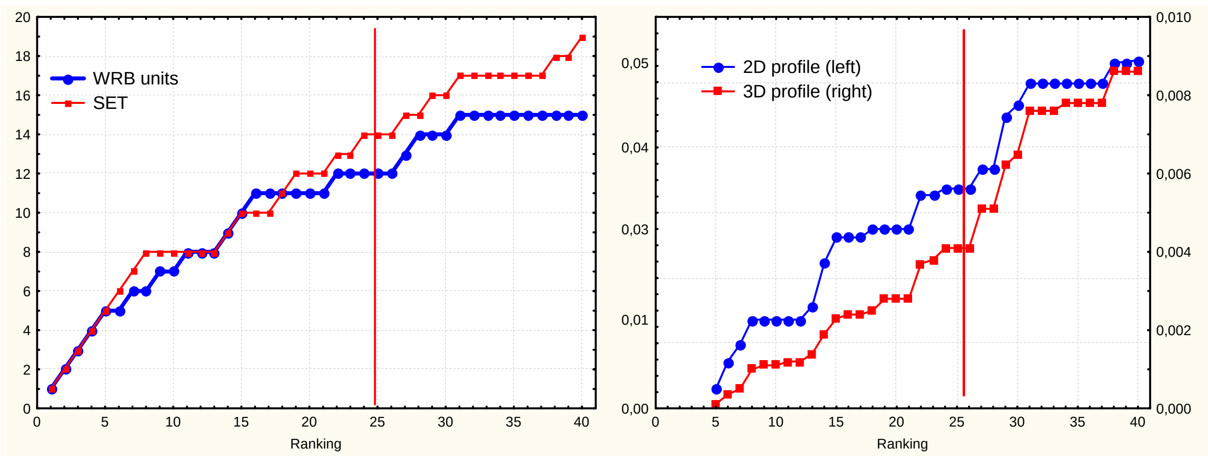


Figure 231 Soil inventory area curves for four different pedodiversity approaches on the obs. #04 Omatako

Here, a comparison of the species area curves of different pedodiversity approaches is given by the example of the observatory #04 Omatako (Figure 231) In general, all curves show the same trend with the most significant increase slump above ranking 31. However, the SET and Parametric space approaches show a continuous increase up to this point, while the WRB approach is declining already above ranking 16. Increases frequently occur in parallel in all approaches (e.g. rank 13-15) but with different intensity. An opposite example is the situation between ranking 8 and 11 where the parametric classification and space approaches remain constant while the WRB units increase. This is a typical effect of WRB qualifiers such as chromic, which are not inevitably combined with a change in parameters.

The graphs are of valuable information for both, the required intensity of the soil survey and the behaviour of the parametric pedodiversity approaches. I raised the question whether the parametric approach with convex hull algorithms could capture the entire variability with fewer samples than the classification approaches. This question was based on the assumption that only few samples (< 10) including all habitats could already suffice to establish the important parametric values reflecting the ranges of the system. However, the curve behaviour of the parametric space approaches in Figure 231 revealed that this is not the case. On the contrary, the increase of parametric space is still evident in high ranking numbers whereas the WRB units remain constant or increase slightly, respectively.

Consequences of this example are only preliminary and a further comparison of such soil area curves for the remaining observatories have to be tested in order to validate the results. From this example, it can be concluded that basic trends in curve behaviour are comparable but that the sensitivity of SET and parametric space is higher, particularly in the high ranking numbers. It has to be tested whether this is still of ecological relevance or solely due to methodology. Furthermore, the example showed that the increase in the less sensitive approach, the WRB units, is declining above ranking 15 but still evident until ranking 30. This underlines the necessity of a detailed survey per observatory to gain a reliable data set of the soil diversity.

6.7 Correlation between Pedo- and Biodiversity

This chapter intends to analyse the correlation between pedodiversity and biodiversity. The basic principle for the analysis is the comparison of the resulting richness per observatory by use of the pedodiversity indices introduced above and the species richness of higher plants.

The distribution and frequency of a species is limited by various environmental factors. Next to primary ecological parameters such as light, temperature, water, and nutrients, indirect factors such as climate, relief, and soil play a major role, especially on the local scale.

Species richness data of higher plants is derived from the monitoring data of the BIOTA Southern Africa subproject S06 (Biocentre Klein Flottbek, Hamburg). Species data is sampled in the same spatial context as the pedodiversity analyses, i.e. on the first 25 hectare plot on each observatory by survey of a 20 * 50 m area on the central position of the hectare. Except for the Cape observatories #32 and #33, for the species numbers are available all selected observatories of this study. However, due to taxonomic and phenological difficulties to date, the data is only usable as a 'best available' status which will improve in the course of the project. The data is currently characterised by following restrictions:

i) the monitoring frequency differs along the transect from site regularly monitored since 2001 and site sampled only once during this period of time

ii) the status of identified species differs from 50 to 100 %, i.e. a number of species unidentified due to the lack of taxonomic reference or difficulties in terms of a precise identification of plants in bad conditions

iii) a small variation in the number of monitored plots between 20 and 25

Nevertheless, the data is reliable enough to start such comparative analyses. In Tab. 14, an overview shows the used original species data, the degree of their identification and the selected adjusted numbers. In case of the observatory # 20 (Numees), an upgrade of the total number of species was necessary due to the fact that the site was only surveyed once and includes only 14 hectare plots. The adjustment with regard to the higher species number is based on previous investigations in the area and the estimation of the responsible botanist. In case of the observatory # 21 (Yellow Dune), a reduction of the total numbers of species over all of the years was necessary, as the species number of the 'best' year indicates lower potential species numbers. The term 'best year' is used here for the year with the highest number of found species. In ecosystems with a high variation in rainfall, this is a necessary step for the comparability of data. Moreover, it is ensured that within one survey no change in surveyor took place. Due to several changes in surveyor at some observatories it is most likely that many species are doubled or even tripled in the database due to different 'draft'-names. For the same reason, the total number of species for all of the years was reduced for the observatories #24 and #25.

Additionally, the observatory #16 Wlotzkasbaken was excluded from the analyses due to the low mean annual rainfall of 10 mm which restricted the development of higher plants.

Tab. 14 Overview of available and adjusted species data (status 08/2007) used for correlation analyses. Bold printed numbers indicate the reduced dataset with 25 soil data information / obs.. Positions highlighted in yellow indicate adjusted species numbers. X indicates the number of changes in the person who surveyed the site.

	No. of Species				Percentage of identified species		
OBS	All years original	Best year original	All years adjusted.	Best year adjusted	All years	Best year	Surveyor change
1	198	169	198	169	99	96	
2	221	160	**221**	**160**	98	94	
3	237	177	237	177	99	95	
4	302	158	**302**	**158**	96	76	XXX
5	341	180	**341**	**180**	91	79	XXX
6	217	140	**217**	**140**	91	79	XXX
10	241	154	241	154	77	68	XX
11	181	114	181	114	77	74	XX
16	28	27			70	71	X
17	109	82	**109**	**82**	71	66	XX
18	198	154	**198**	**154**	47	46	XX
20	177	177	**320**	**300**	79	79	
21	270	121	150	121	50	39	XX
22	531	416	**531**	**416**	60	56	
24	581	352	**500**	**352**	68	50	X
25	610	379	**500**	**379**	69	52	X
26	298	254	298	254	84	77	
27	308	251	308	251	79	70	
39	153	118	**153**	**118**	93	87	X
40	155	130	**155**	**130**	89	83	X

Original and adjusted data for all recorded species over all of the years as well as for the number of recorded species in the 'best' year were used for the correlation analyses with pedodiversity results. In order to gain a most reliable database the analyses were split into three branches: i) all available data pairs (n=19), ii) only observatories with comparable number of 25 profiles (n=12, bold printed in Tab. 14) and iii) only observatories with comparable numbers of 25 topsoil datasets (n=16).

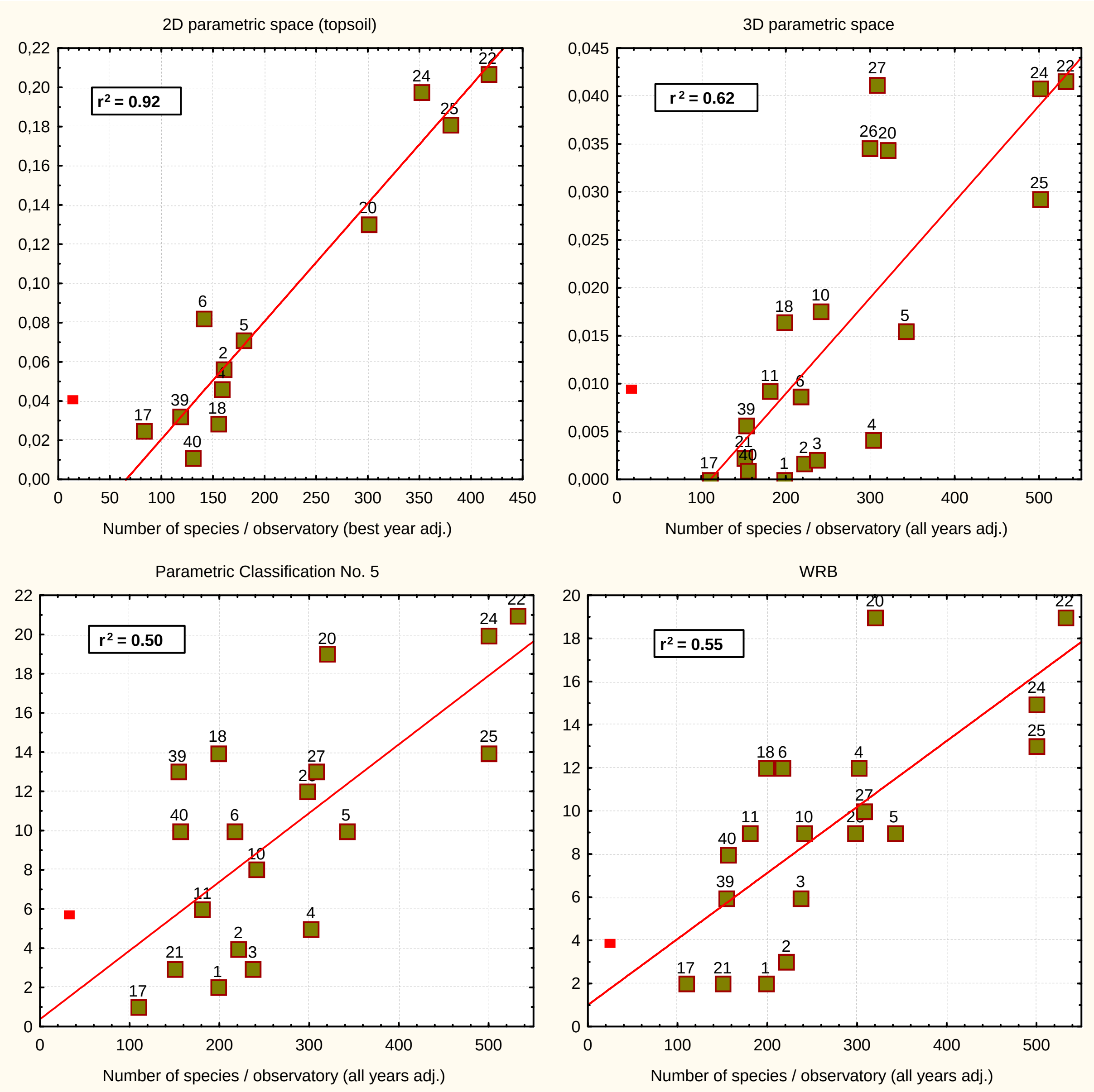


Figure 232 Selected correlation graphs of species numbers per observatory and different pedodiversity approaches. Red marked square is the excluded observatory #16

Figure 232 and Tab. 15 show the results of the correlation analyses which show an overall high level of significance for the positive relationship between pedo- and biodiversity (here species richness). Highest r-squares are reached by the parametric space approaches while the WRB and parametric classification approaches show lower values.

Highest values across all approaches are evident in the correlation to 'best year^{++}', the data restricted to observatories with 25 sample points, i.e. the best quality database. Here the 2D convex hull approaches reach r-squares of 0.92. An interesting feature here is the decrease of r-square with an increase in dimensions in the convex hull approach. This is most likely a mathematical effect of a relative increase in differences of resulting values leading to weaker r-squares.

Tab. 15 Correlation between selected pedodiversity approaches with phytodiversity data

	N=19+		N=12++		N=16+++ (topsoil)	
R^2	All years+	Best year+	All years ++	Best year ++	All years+++	Best year +++
2d_chp	0,67***	0,81***	0,81***	0,92***	0,66	0,83
3d_chp	**0,62*****	0,74***	0,76***	0,86***	0,61	0,76
4d_chp	0,77***	0,83***	0,76***	0,83***	0,76	0,83
5d_chp	0,69***	0,67***	0,71***	0,71***	0,69	0,66
2d_cht	0,44**	0,55***	0,88***	**0,92*****	0,41**	0,53**
3d_cht	0,21*	0,30*	0,76***	0,83***	0,18	0,28*
4d_cht	0,48***	0,61***	0,71***	0,81***	0,45**	0,59***
1_PP	0,38**	0,38**	0,35*	0,44*	0,36	0,42
2_PP	0,41**	0,38**	0,41*	0,45*	0,41	0,44
3_PP	0,40**	0,40**	0,36*	0,45*	0,38	0,45
4_PP	0,52***	0,61***	0,49*	0,67***	0,50	0,66
5_PP	**0,50*****	0,59***	0,45*	0,61**	0,48	0,64
1_PT	0,36**	0,37**	0,62**	0,66***	0,35*	0,40**
2_PT	0,35**	0,35**	0,62**	0,64***	0,32*	0,37**
3_PT	0,45**	0,48**	0,67**	0,74***	0,45**	0,53***
4_PT	0,53***	0,66**	0,59**	0,72***	0,52**	0,69***
5_PT	0,44**	0,62***	0,56**	0,79***	0,42**	0,66**+
WRB (2)_	**0,55*****	0,53**	0,52**	0,61**	0,52	0,56

(*** = p <0.001; ** = p < 0.01; *= p < 0.05)

+ including 19 observatories with few obs with less than 25 profile

++ including 12 observatories with 25 profile

+++ including 16 observatories with 25 topsoil

xd = dimensions, chp = convex hull profile, cht = convex hull topsoil, PP = Parametric Profile, PT = Parametric Topsoil,

7 Concluding discussion of applied pedodiversity analyses

Pedodiversity can be defined as an integrative description of soil properties for a specific area. It can thus be used for comparative diversity analyses. Although the term has not been defined in literature to date, the analyses in the previous chapters will contribute to the development of an integrative pedodiversity measure.

Pedodiversity as a relative measuring tool always needs to be adjusted to the scientific aims and objectives. For the study region, the central issues are biodiversity prediction and land-use impact. With respect to a more general application of the derived pedodiversity indices, an evaluation of the indices is discussed in the following according to

i) the requirements of data and methodology,

ii) the ability to differentiate various areas,

iii) the correlation to phytodiversity,

iv) the comparison with previous approaches.

7.1 Data requirements and methodology

The results of this thesis show that a high soil survey density is necessary to capture the variability of a given system of 100 ha in size. This is true for all tested approaches, even for the most basic approach of WRB units with only one qualifier. The soil unit area curves indicate a relatively complete capture of soil variation in many of the sites. Some observatories show steep pedodiversity increases within the higher-ranking numbers from 15 to 25. By restricting the number of profiles to 25, an underestimation of the pedodiversity has to be stated for these sites. For the observatory #04 (n = 40), the underestimation could be quantified to ≥ 3 WRB-units and ≥ 50 % of parametric space. The other extremes are represented by the sites with very homogenous substrate conditions such as the dune sites in the Kavango and the Kalahari. Here, with a number of 25 profiles, an overload of field and laboratory work is evident. The entire diversity of WRB units and the maximum of parametric space can be derived from 7-14 profile data sets on these sites only. Thus, for studies in these systems a restriction in the survey intensity to 15 ranking numbers would suffice. This example indicates that the sampling effort has to be adapted to the system studied and the area size regarded. Therefore,

The assessment of pedodiversity for the study region requires a high information density general recommendations regarding the necessary sampling intensity cannot be deduced. In the context of this study, the applied intensity of 25 profiles per square kilometre can be regarded as a sound compromise between data requirements and feasibility of field and laboratory work.

Next to the profile density and the reliability of resulting diversity, a number of further features have to be considered. The applied ranking procedure is stratified random sampling, which forces small habitats into higher ranking positions than random selection in order to also capture smaller units within a reasonable sampling magnitude. However, this advantage aside, the procedure weights smaller units stronger than larger units in higher ranking positions (see chapter 2 for explanation). This results in a steeper soil area curve (and also species area curve) compared to simple random sampling within the square kilometre. For extrapolation purposes, it is therefore recommended to recalculate the relative abundance of soil units according to the proportion of habitats in cases with a strong relationship between habitat and soil properties.

The different degrees of patchiness in soil properties may have a major impact

During the study, the degree of patchiness and the patch size of plant and soil patterns revealed to be another important topic that has to be discussed with respect to the applied methodology. In particular within the southern part of the transect, many sites are dominated by small-scale changes (1 – 10 m) in soil properties and plant communities. Examples are the observatories #22 Soebatsfontein (see also HERPEL in prep.) with a high impact of heuweltjie structures and the observatories in the Knersvlakte (#26 and #27) with small-scale changes in pH-values and salt content. These changes occur within few meters and lead to difficulties in the causality analyses of soil plant interaction due to spatial differences in soil and vegetation sampling. For those systems, it might be helpful to implement an additional small-scale cluster sampling method as proposed by HOWARD and MITCHELL (1985) in order to strengthen the data for on plot causality analyses. Additionally, information about mean patch sizes and their spatial distribution could add general information on the soil structure of the observatory. Another aspect is the frequency of occurrence of such patches (e.g. one heuweltjie compared to 300 per observatory). For the interpretation of these features, it is important to provide parametric data with statistical values (e.g. Box-Whisker Plots) in addition to the integrative pedodiversity indices. With respect to the correlation analyses on the square kilometre level applied in this study, the spatial patch structures do not influence the overall results. The high sampling intensity ensures a capture of all the important units irrespective of their frequency of occurrence and spatial distribution.

The derivation of pedodiversity indices from WRB soil units on the one hand and from measured (top-)soil properties on the other hand are different in procedure but have similar operating expense. Specialists are required for both tasks, as in general the analysis of soil properties is not reliable if sampling has been carried out without expertise. Looking at the taxonomic classification pedodiversity approaches, it has to be taken into account that even for the derivation of soil units some soil analysis seems to be of paramount importance. For instance, the qualifiers ’Eutric and Dystric’ cannot be applied if there is a lack of knowledge regarding pH and base saturation. This means that even for the application of the ‘simple’ taxonomic approach, data on different soil properties has to be analysed in the laboratory. Few situations may allow a lower number of analyses such as base saturation in a coarse textured humid environment that is overall ‘dystric’. However, for a reliable classification other analyses with comparable effort are then required. In summary, the three tested approaches are comparable in terms of labour intensity.

7.2 Sensitivity of methods

The present study employs the term sensitivity in two ways. Firstly, sensitivity describes the ability of the different methods to differentiate between high and low pedodiversity of the areas involved. This has to be regarded for all classification methods where the class sizes are defined individually according to the scientific objective. Secondly, it has to be considered that the pedodiversity indices react more or less sensitively to the change of different soil parameters. This is especially true for the taxonomic approaches and has been discussed in the results for the WRB classification and the parametric classification.

For the application of these quantitative pedodiversity methods, it is essential that the method offers sufficient sensitivity and that the influence of soil parameters on the results is established, for instance if variations concentrate around class borders or if they cause shifts in qualifiers because of only minor changes.

Sensitivity includes both, the ability to differentiate and the potential to reflect changes

For the parametric classification established in this study it was necessary to find a compromise between a high sensitivity (i.e. small classes) and a high range of soil-eco-types (SET) in the entire data set along the transect while keeping a reasonable mean value of SET. In Tab. 16, the parametric classification approach 5 emerges as the best combination of a mean SET value of 10 similar to the centre of the range and a high standard deviation indicating a good stretch of the data set.

Tab. 16 Range, Mean, and standard deviation of the taxonomic (WRB) and parametric classification approaches including all selected observatories

	Range	Mean	Standard deviation
WRB	18	9	4.8
Para Class.1	23	15	5.89
Para Class.2	20	12	5.3
Para Class.3	21	13	5.99
Para Class.4	20	11	5.68
Para Class.5	20	10	5.60

The three different pedodiversity index approaches are compared in order to identify the major differences, trends and typical sensitivities in behaviour. In Figure 233, two of the selected approaches from the parametric classification and the parametric space index are compared at a time with respect to taxonomic pedodiversity based on the WRB (FAO 1998) soil units on the 2nd qualifier level.

In general, the parametric classification approaches reach higher r-squares than the parametric space approach. This is due to the fact that the counting of objects of the parametric classification results is not able to identify the distances between the counted objects (soil-eco-types). This is, however, a fundamental feature in the parametric space approach. The analogy of the parametric and the taxonomic classification is therefore based on the classification system. This also becomes clear with the same r-square of different approaches (Parametric classification 1 & 5).

In comparison, the WRB system results in relative higher values for some summer rain observatories, especially for the observatories #03 and #04. This is due to the dominance of qualifiers such as ‘rubic’ or ‘chromic’ which in many cases do not reflect ecologically relevant parametric differences. Moreover, the arbitrary differentiation in Luvisols and Cambisols due to marginal topsoil texture differences enhances the number of soil units on the observatory #04.

As a contrary example, the existence of only few dominant diagnostic criteria in the WRB system forces profiles into soil units that do not allow a further detailed differentiation by ecologically important qualifiers. These sites then remain lower in their number of WRB units compared to the parametric classification. However, these relative increases in number of SETs are to some extent a result of variation around class borders. The example of the observatories #39 and #40 illustrates this effect. Whereas these sites reach a comparably high number of SETs within the correlation analyses (above trend line) between WRB and parametric space, they contrarily reach relatively low values in correlation to the parametric space (below trend line).

Relatively high values for the winter rainfall observatories in the parametric space approach are due to high ranges in pH, EC, and organic carbon, which are not very well reflected by the WRB system. In particular the degree of salinity is separated into very rough classes without the capacity to express its ecological importance. The high values in the winter rainfall observatories reflect the major advantage of the parametric space classification, i.e. the recognition of distances in the classification. Therefore, all ecotones within these distances are included virtually in the result. On the contrary, the WRB and the parametric classification are not able to reflect this.

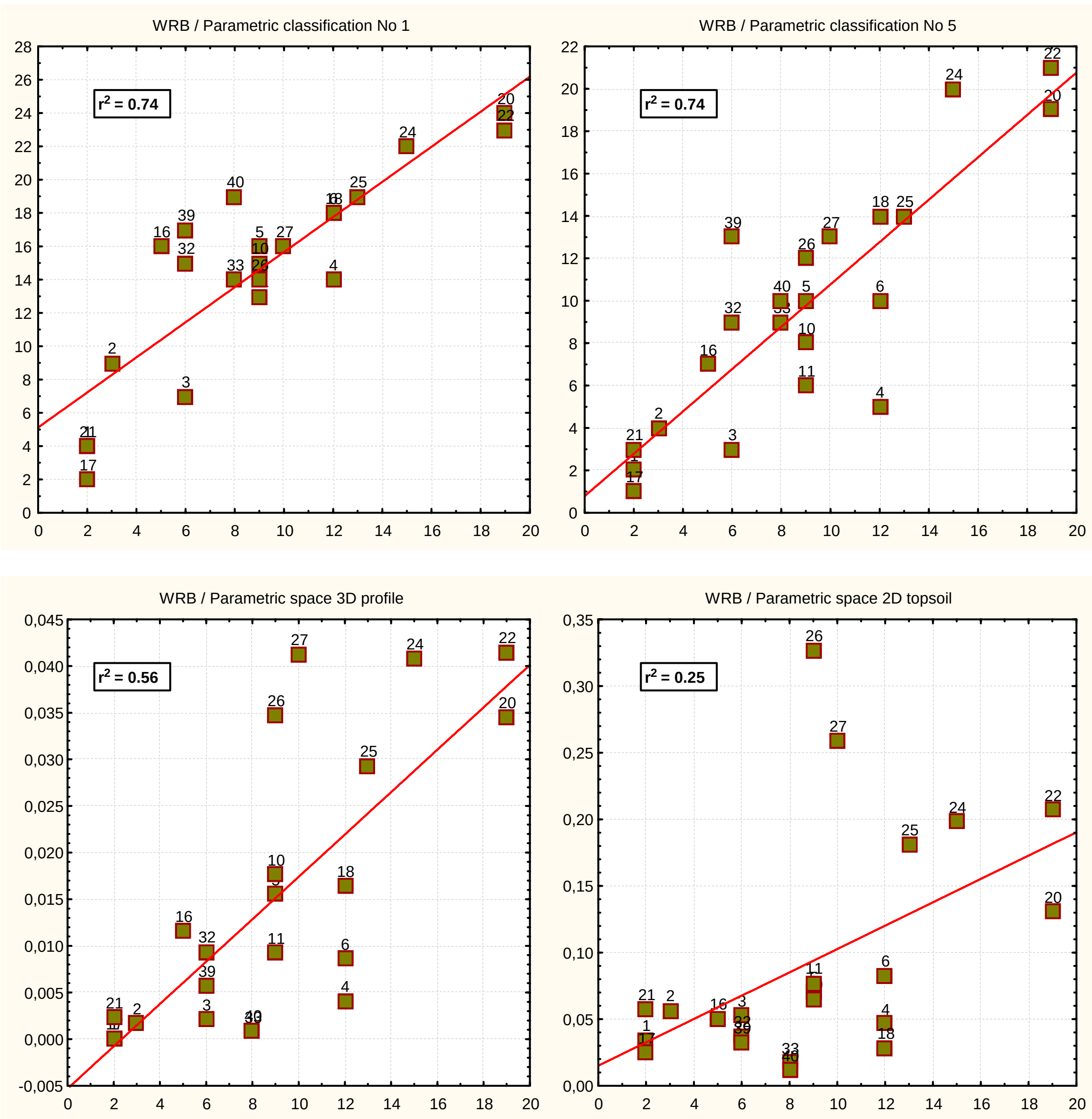


Figure 233 Correlation of selected parametric classification and parametric space pedodiversity results with results of the WRB classification (1998, 2nd qualifier level, number of soil units on x-axes)

Parameter based methods of measuring pedodiversity are more precise for ecological characterisation

In summary, pedodiversity cannot objectively describe soil variation per se, as different classification systems will generate different results for pedodiversity. The sensitivity of methods depends on the applied approach. In the case of parametric classification and parametric space, the sensitivity can be adjusted according to the natural system or the research question, respectively. The internationally fixed reference system of the WRB classification does not allow any adjustments. For comparative analyses on regional levels, the application of a WRB based pedodiversity index seems to be rather useful as this information level is the best and often the solely achievable. This index is probably best applicable for temperate regions where the WRB system is more detailed. For precise ecological studies, the parametric classification and the parametric space approaches are considered as more significant, esp. for drylands as shown in this study. Results of SALDANA and IBANEZ (2007) also demonstrate the important difference between taxonomic pedodiversity and parametric variability. In order to derive final recommendations further research in further ecosystems with different climatic conditions is necessary. Reaching a final conclusion which index is the best recommendation for overall pedodiversity measurement is not possible due to the lack of a reference proof.

7.3 Correlation to phytodiversity

Next to the development of methods for the quantification of pedodiversity, the major aim of this study was to identify the best approach for comparative pedodiversity-biodiversity analyses. The analyses in chapter 6 provide the basis for the following discussion of the correlation results and the recommendations for a suitable index for biodiversity analyses.

During the study, it became apparent that the use of combined diversity indices such as the Shannon or Simpson index is not useful as these indices merge richness and evenness information. Merging the two might be helpful for a quick assessment of assemblages with high numbers of species and individuals. This is, however, not true for the purpose of pedodiversity analyses in this study. Here, the combined indices would lead to a loss of information. Additionally, they strongly correlate with richness or evenness. It is therefore suggested to rather use richness values as a single parameter in the classification approaches. The evenness provides valuable additional information on the abundance pattern within an observatory and can be added separately. However, the interpretation of evenness on broader local landscape levels, as in this study, may be inadequate as the index is strongly influenced by the sampling procedure which favours rare units in the survey of low ranking numbers (see also chapter 7.1).

To date the results of correlation analyses can only be interpreted preliminary as the phytodiversity data set of the botanical BIOTA subproject has not yet been completed. The results indicate significant basic trends in the relationship between pedo- and phytodiversity which are expected to become more precise subsequently for improving the botanical database. The most significant correlation is achieved by the pedodiversity approach 'parametric space' using convex hull algorithms and the reduced database with observatories including 25 profiles. Within this approach, the 'best year' phytodiversity data (year with highest number of counted species) achieved the most significant correlation with pedodiversity. I interpret these 'best year' species data as the most reliable as it is ensured that no doubling or tripling of species names occurs and the sampling effort for each observatory is comparable. High correlation is evident for the parametric classification approach 4 (profile) and all parametric classifications using topsoil data.

The parametric space approach using convex hulls achieves the highest correlation between phyto- and pedodiversity

As shown in chapter 6.7, with the parametric space (i.e. convex hull) approaches the plant species richness is predictable with an accuracy of more than 90 %. The best results were achieved by using the simple approaches applying only pH and EC (2D) as parameters. Further tests with other data sets will have to validate this finding and also the influence of the mathematical laws regarding the n-dimensional space on the results has to be investigated further. If this predictability turns out to be true, this will most probably have implications for the sampling scheme and effort. Laboratory and fieldwork for the estimation of pedodiversity of a specific area could then be reduced considerably. Of course, this would only be true for the overall estimation of soil variation and would exclude the possibility of plot-related causality analyses between soil and organisms.

Next to the existing corrections and restrictions discussed above, some basic problems in the correlation analyses between bio- and pedodiversity shall also be mentioned here. A general issue in diversity studies is that one needs to distinguish between long-term evolutionary effects in the group of organisms and recent influences of the abiotic and biotic environment. When regarding a specific area like a biome or region, the vegetation composition is mainly driven by macro ecological parameters like temperature and precipitation regime and historical factors such as evolution. It is possible that taxonomic diversity at the general level is linked to the evolutionary development over long periods of time, whereas taxonomic diversity at the species level corresponds to the parameters of abiotic heterogeneity or geodiversity (Richter 2001). Additionally, there are intra-community mechanisms like competition, predation, parasitism and mutualism and also human activities due to utilisation, fragmentation etc. (see Figure 234). The relationship between resources, species interactions and species abundance is the key to the notion of the characteristic patterns of diversity (Magurran 2004). Finally, it shall be mentioned that within one parameter different species respond

Species diversity is a combined result of evolution, biotic and abiotic influences to changes to varying degrees. At the same time the kind of parameter may affect certain species stronger than other, e.g. water overrides nutrients or vice versa (see also WIJESINGHE et al. 2005)

As several autocorrelations may exist, correlation with environmental factors always uses a 'relative' number of species. The resulting diversity is a combination of the regional to microhabitat features and the overall 'species pool' limited by macro ecological processes (evolution, climate). Human induced invasive organisms may play an additional role in the 'species pool'. Comparisons of two regions according to species numbers may be problematic when comparing sites driven by different macro ecological features, especially evolutionary aspects, and comprising very different 'species pools'. A good example is the comparison of sites in the Paleotropis and the Cape Floral Kingdom (CFK) both having a substantially different evolutionary history and consequently a very different number of species on a regional scale. A mere comparison of species numbers of specific sites may result in higher species richness for the CFK site due to the greater variety in its species pool. At the same time, taxonomic distances and (abiotic) habitat diversity may be superior on the site with fewer species. This hypothetical example will be proofed in future in course of the project but is not yet included in the database.

Comparison of mere species numbers have to consider the regional 'species pool'

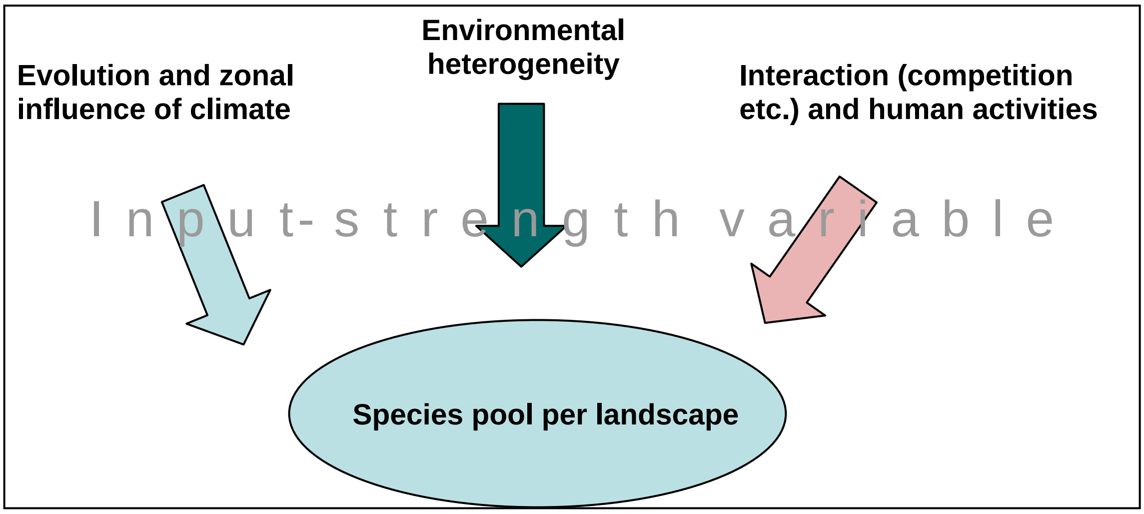


Figure 234 Simple scheme of biodiversity influencing factors

Nonetheless, studies of COWLING et al. 1996, COWLING & LOMBARD 2002 and RICHARDS et al. 1995, showed that heterogeneity is an important predictor of plant diversity on the <u>regional</u> scale. Even <u>local</u> changes in e.g. soil properties - and may they only be subtle - can lead to changes in species composition. THUILLER et al. (2006) emphasise the dominating importance of the topographic heterogeneity in shaping the spatial pattern of regional plant species richness for different biomes in southern Africa.

Their findings are based on standard deviation of height measures in a 200 x 200 grid within a 25 x 25 km cell. Although topodiversity has also been recorded in this study (see chapter 6.5), the applied scale of 1 km^2, and the preference of more levelled landscape units where available, biases the results in advance. Topodiversity used here is therefore rather a descriptive parameter for the site characterisation. In the few cases of evidence (mountainous observatories) such topographic influences are mirrored by the corresponding soils and thus incorporated in the analyses. Though topographic heterogeneity is strongly correlated with pedodiversity and often used as overall measure for abiotic diversity, it may lack information on the lithology and local pedodiversity caused by biotic interaction such as termites or subtle small-scale changes in nutrient and salt dynamics. Analyses of phytodiversity and means of topodiversity (mean, median, standard dev., and range in height of the observatory and on 100 m distance, see chapter 6.5) revealed much weaker r-squares of 0.3 to 0.5 than the pedodiversity analyses. Thus, the advanced pedodiversity indices based on the soil inventory of landscape units including information about lithology and local soil diversity may significantly strengthen the topographical approach for a characterisation of environmental heterogeneity.

Abiotic diversity is strongly influencing biodiversity on the micro to local scale

In biodiversity studies, and here in particular in phytodiversity analyses, there is an ongoing debate to which degree the current environment on the one hand and its history on the other hand shapes the biodiversity of a given area (MUTKE & BARTHLOTT 2005). The question of scale has to be handled carefully in these discussions as either factor may be dominating depending on the regarded research area. PEARSON and DAWSON (2003) assume soil type and biotic interaction to be the most important factors affecting species distribution from the micro- (< 10 m^2) to the local scale (1 – 100 km^2). They recommend further research in the analyses of scale relevance of the different environmental drivers such as soil and topography.

Integrative pedodiversity indices may enhance characterisation of environmental diversity

FAITH & WALKER (1996) and FAITH et al. (2004) recommend a surrogate approach for the determination of environmental diversity (ED), incorporating any available information for a reliable proxy for species richness estimation. ARAUJO et al. (2001) tested this approach with European data and found only weak support for the hypothesis. However, the applied data may not be representative for other regions, as the European environment is strongly affected by human history and change of natural environment. Additionally, with the applied scale using regional driven parameters such as evapotranspiration, precipitation and temperature, it is not adequate to include the expected local influence of environmental heterogeneity assumed to be significant for local species richness (e.g. small scale topography, lithology etc. mirrored in pedodiversity). Integrative pedodiversity indices will provide useful information for such approaches, as they are not susceptible to information loss on higher scale levels.

Differences between biotic and abiotic groups or parameters are also evident in scale-related terminology. For biodiversity, the terms alpha, beta and gamma diversity are applied for different spatial scales. Whereas alpha diversity is described as within plot variation, beta diversity describes "between habitat diversity" and gamma diversity is used for local to regional diversity. The deviant terminology and scale concerning the soil information in this study is due to the different sampling techniques that comprise pedon-related soil information on the smallest scale as single soil information. Notwithstanding, the accompanying vegetation sample consists of communities. These can be assigned to alpha diversity and the total information of an observatory can be regarded as gamma diversity. However, for the soil information, only the entire number of soil units of an observatory can be regarded as alpha diversity, i.e. the smallest sampling unit comprising a number of objects. Depending on the study region, this concept will have to be adapted carefully. It is highly probable that a higher soil sampling intensity within a vegetation plot may comprise an on-plot alpha diversity related to that of the given plant community. Small-scale investigations along transects revealed the importance of such variation in certain regions (e.g. Namaqualand). Furthermore, another study within our research project (HERPEL, in prep.) focuses on this small-scale variation. The results indicate that in many cases alpha-pedodiversity is linked to alpha phytodiversity but cannot be generalised. In some regions, e.g. Kalahari dunes, small-scale variations in soil properties are missing and hence do not account for the alpha diversity of plants. Here, processes such as succession, competition, disturbances etc. govern the small-scale (alpha) diversity.

Pedodiversity per observatory can be regarded as soil 'alpha diversity'

Analyses of relationships between pedo- and biodiversity on a non-species related scale can be carried out when using plant communities or functional traits instead of species numbers in order to increase the explanatory power of the correlation. For this approach, the species recorded on the observatories are grouped into phyto-sociological communities, taxonomic groups or assigned to functional traits. This grouping can then be used for causality analyses on the plot scale as well as to reduce the inevitable evolutionary aspect of different species pools mentioned above. Especially for the winter rainfall area, which comprises a high number of species, this can be considered as a useful approach. Many of the species occurring there (e.g. in the family of Ericacea) seem to have very closely related ecological requirements and therefore do not represent wide abiotic ranges in site properties in comparison to the similar number of species in another region. In general, it needs to be stated again that taxonomic distances within species taxonomy are still not easy to define.

Phytodiversity described by plant functional types may provide better ecological characterisation of a specific site

Almost similar limitations are evident when comparing the evenness of soil types with the evenness of phytodiversity within an observatory: Evenness of the phyto-component can only be compared with pedo-evenness when the species per plot have been grouped into communities and the number and abundance of communities was used for the calculation of diversity and evenness. When using all species numbers from the observatory in one pool, the species pattern is potentially reflected in an inadequate context. As an example, two different soil profiles reflecting two microhabitats resulting in a high evenness on the km^2 shall be regarded. Assuming two completely different vegetation communities on these microhabitats with i) three trees and ii) 100 bushes, one can calculate evenness in terms of plant communities which also would result in a high evenness and would reflect the ecological situation of an equal proportion of two habitats. The typical way of calculation, however, would take all plant individuals per km^2 into the data set and calculate the evenness in this total population, which would result in very low evenness values due to the dominance of the bushes. This effect would already be levelled out when using the relative abundance instead of the species numbers.

7.4 Conclusion and perspectives

To date, pedodiversity studies have been applied in various contexts and on various scales, predominantly concentrating on regional, national or continental levels. This study aims at contributing to the discussion of methodology as well as to the knowledge of soil properties and soil diversity on a relatively small scale of 1 km^2. For the study region, this scale reveals highly relevant information about soil diversity for both, the comparative pedodiversity analyses along the transect and for the analysis of the local soil pattern. The latter contributes to a large extent to the relatively limited knowledge of soils in the study region.

This study reveals new possibilities for pedodiversity analyses

As the whole pedodiversity concept is still under a vivid discussion (e.g. IBANEZ et al. 1995, IBANEZ & RUIZ-RAMOS 2006, CANIEGO et al. 2006), particularly the newly developed approaches of this study and their application to a highly reliable and comparable database can contribute to the methodological development of pedodiversity. The present study managed to show that a strongly parametric orientated index is generally advantaged in comparison to other established classification systems such as the WRB. On the other hand, the application of the WRB system on a small scale of 1 km^2 showed to be sensitive enough for pedodiversity analyses on these scales. The findings of SALDANA and IBANEZ 2004, IBANEZ et al. 2005, CANIEGO et al. 2006, IBANEZ and RUIZ-RAMOS 2006, which observed that soil inventories often behave like power laws known from the biotic communities, could also be confirmed in this study for both, the taxonomic and the parametric classification.

Up to now, most of the pedodiversity analyses (see literature review on pedodiversity) used large-scale approaches by incorporating existing national or international soil databases. Only few studies analysed pedodiversity on a smaller scale using appropriately derived data (e.g. SALDANA & IBANEZ 2004, SCHARENBROCH & BOCKHEIM 2007, PHILLIPS 2007, MCBRATNEY & MINASNY 2007 and TOOMANIAN 2007) and recognised a significant pedodiversity on the small scale in different ecosystems. The results of this study support these findings. This is particularly interesting, as typically drylands are assumed to feature low pedodiversity. Such assumption is, however, an effect of a failure of common classification methods with regard to the recognition of ecological important parameters in drylands, as well as due to soil survey intensities that were too low in these regions.

The methodology applied in this thesis, using standardised soil surveys with subsequent ecological interpretation of the individual observatories, was able to contribute considerably to the knowledge about soil spatial patterns and soil properties in the study region. It revealed both, specific regional trends in soil properties as well as observatory-specific information about the spatial scale of changes in soil properties and the main ecological drivers behind these patterns.

General restrictions in the development of pedodiversity indices arise from their dependency on the spatial distribution of the data set as well as the survey intensity (HUDSON 1998). The standardised methodology applied in the BIOTA Southern Africa project avoids such problems as it produces a homogenous data set for the macro transect which allows the generation of comparable pedodiversity indices. Therefore, pedodiversity indices can be calculated that are applicable from the local to the regional scale and allow a direct comparison with vegetation data.

A direct comparison of the results of this study with literature is not considered useful as the results strongly depend on the applied scale and the survey intensity. For such comparison, a general fit of the databases to similar basic conditions would be necessary prior to any analysis. Generally, when comparing classical diversity indices, a split into richness and evenness values is important to interpret which value dominates the combined diversity index. As IBANEZ et al. (1998) showed, mountainous regions obtain the highest number of soil units but show the lowest diversity value because of their low evenness.

Despite the surge in biodiversity studies, pedodiversity analyses in combination with phytodiversity data are rare. NICHOLS et al. (1998) and BURNETT et al. (1998) for instance studied the influence of geomorphological diversity on vascular plant species on Rhode Island and found that soil drainage classes account for more than 50 % of the variance in total plant species richness. They conclude that biotic and abiotic diversity are intricately linked on the landscape scale and that the conservation of geomorphological heterogeneity may therefore be an effective strategy for conserving biodiversity. MUSILA et al. (2005) describes mutual dependencies of soil properties and tree diversity in a western Kenyan rainforest and recommend to intensify studies on geodiversity in ecological research.

The study enabled for the first time reliable comparison of pedo- and phytodiversity data along the BIOTA transect

Results of pedodiversity analyses in this study enable correlation analyses of pedo- and phytodiversity data for the study region for the first time. At the same time, the results prove the chances and possibilities of integrative abiotic characterisation by the use of soil data as highlighted in the literature discussion (chapter 5.4). The developed pedodiversity methods provide the possibility to predict the potential number of vascular plants of an area and to compare predictions and real findings. As pedodiversity is a more stable landscape property as biodiversity, this enables the detection of local or regional human impact on biodiversity (e.g. overgrazing with shifts in species number or species composition). One important future analysis within the BIOTA project is therefore the differentiation of pedodiversity and phytodiversity analyses using annual and perennial species.

In this study, the simple correlation of overall species numbers and pedodiversity (here richness) per observatory already revealed highly significant positive results which encourage further research in the correlation analyses of phyto- and pedodiversity. Regarding the database of BIOTA Southern Africa, it is planned to create regional subsets for the correlation analyses in order to minimise the overall climatic impact and different evolutionary histories. Further research is also necessary with respect to the application of the developed approaches on other ecosystems with different climatic conditions. Here, the most restricting factor will be the availability and reliability of data. In general, the measurement of biological richness and diversity is a costly and time-consuming process. The use of existing abiotic data and / or the easier assessment of these data sets might be an alternative for conservation analyses.

Besides the discussed relationships between pedo- and biodiversity and possible causality analyses with regard to biodiversity and conservation issues, the value of pedodiversity is in its integrative character. Pedodiversity indices are of high value because they can be used for several applications such as the quantification of landscape heterogeneity, the description of variation within soil mapping units and the estimation of the loss of information in generalisation processes. This was also recently recognised by SCHMIDT and JAHN (2004) with regard to the discussion of restructuring the German soil classification system.

Functional and taxonomic distances in diversity measures have to be developed

With respect to causality analyses of diversity trends in plants, a general discussion of the possibility to separate the causes and trends for phytodiversity on different scales is provided by RICKLEFS (2004). He questions whether it is possible to quantify the influences of history, environmental heterogeneity and community interaction and stresses these issues as important future research fields. In order to enhance the power of diversity measures, the inclusion of functional and taxonomic distance aspects may provide a better environmental correlation than the frequently used richness and evenness based diversity indices. For the soil sciences, this aspect has recently been raised by MINASNY & MCBRATNEY (2007) when they incorporated taxonomic distances into pedodiversity analyses. RICKLEFS (2004) points out that diversity measures shall not be used as an overall toolbox for any ecological or nature related economic field such as agriculture. However, diversity measures have proven to be of great importance for environmental assessments and monitoring research as well as comparative analyses and ecosystem function (RICOTTA 2005).

The understanding of soil / water dynamics in drylands is of crucial importance for future pedodiversity analyses

In addition to these methodological perspectives, a crucial point for further understanding of dryland ecosystems is the functional aspect of water supply. According to the global change scenarios, southern Africa will experience both, an increase in temperature and a decrease in precipitation (IPCC 2007, DE WIT & STANKIEWICZ 2006). Furthermore, many regions will experience an increase in intensity of rainfall events. From a soil science view it is necessary to raise the importance of this combination of factors which will increase the predicted loss of 10-20 % of rainfall to considerably higher values. Higher intensity of rain events will increase water runoff and probably increase erosion rates while higher temperatures increase the evaporative loss of infiltrated water. This scenario is generally affected by an increasing land-use intensity and its influence on soil surfaces as an important and highly variable microfeature affecting the small-scale distribution of water (pedoderm, see FEY et al. 2006, MILLS et al. 2006). It is recommended to include such surface structures as a parameter in pedodiversity analyses. The functional diversity of water supply driven by soil properties in drylands will therefore be important for future research and modelling approaches regarding biodiversity and climate change scenarios.

Quality and functional aspects of pedodiversity are important future research fields

As a concluding remark, the importance of pedodiversity quantification techniques needs to be stressed again. Although technologies and indices are not frequently considered to have an intrinsic value, a large variety of ecological questions, processes and problems receive valuable information by indices, similarity comparisons or multivariate techniques. Given the recent attention paid to the role of diversity in ecosystem function (e.g. LOREAU et al. 2001), the importance of variation in environmental factors for diversity variation needs to be stressed strongly. The philosophy of pedodiversity has to be strengthened by emphasising the ‘quality’ of the ecological significant variability within the pedosphere. There is a wide field of unrecognised difference between measurement and evaluation of the diversity of classification results and their value for ecosystem functions. For further acceptance and development, this concept of ‘functional diversity’ demands greater attention and research regarding the evaluation of ecosystem services. The overall value of pedodiversity analysis approaches chosen and discussed in this study is in the contribution to the debate on the nature and measurement of important abiotic diversity variables. Moreover, this study was able to offer new alternative approaches to diversity measures such as the ‘parametric space’. These will have to be further tested in future. Present results of this thesis encourage to reconsider the established diversity measures and to explore new approaches in ecological research.

During the completion of this thesis, the title of Nature in September 2007 (Nature 449) ‘*Reading the signs*’ raised the importance of monitoring and assessing phytodiversity patterns that could provide warning signals for changes. These patterns are inevitably linked to underlying soil patterns in arid and semi arid ecosystems, which cover around 40 % of the Earth's land area and are home to over two billion people (SOLÉ 2007, KÉFI et al. 2007).

As highlighted throughout this thesis, pedodiversity is thus not only an academic exercise but provides an important future tool for ecosystem characterisation and understanding. The loss of biodiversity and desertification are always combined with changes in soil properties and soil resources. Understanding these connections is a prerequisite for the sustainable use of natural resources.

8 Summary

Soil represents the critical interface between atmosphere, lithosphere, biosphere and hydrosphere and is thus an ideal integrative component reflecting the variety of influences. Moreover, it is the most important resource for biotic components and thus strongly affects biodiversity. On local to regional scales, abiotic environmental heterogeneity is assumed as the most important driver for species richness and patterns besides biotic population interaction. Pedodiversity is a way of measuring soil variation and can be used as an integrative index for soil information and comparative diversity analyses. Pedodiversity can be regarded with respect to different aspects such as taxonomic, genetic, parametric and functional diversity. Understanding and maintaining ecosystem functions are the primary purposes of pedodiversity studies using relatively new techniques for the assessment of soil variability.

This thesis aims to analyse the pedodiversity of defined dryland areas in southern Africa. The study contributes to the understanding of soil diversity (pedodiversity) and its significance for the ecosystem. The first major aim of this study was to close the gap of knowledge regarding the distribution and pattern of soils on both, a habitat orientated local scale (< 10 m – 1000 m <) and a sub-continental scale by analysing 22 survey sites (biodiversity observatories) of 1 km^2 in size along a transect of 2,500 km from Northern Namibia to the Cape region. In order to apply a comprehensive approach for the quantification of the abiotic diversity, the second major aim of this study focuses on the methods to quantify pedodiversity. The further development of criteria for pedodiversity and the relation of parameter-orientated pedodiversity indices to biodiversity will provide a future tool to quantify the relationship between pedo- and e.g. phytodiversity and will help to discriminate between the influence of soil and other factors.

The study is embedded in the BIOTA Southern Africa project, an interdisciplinary research approach with focus on monitoring ecosystem functions such as biodiversity under different land-use aspects (www.biota-africa.org). The study area is located in southern Africa stretching from Northern Namibia to the Cape region covering all major biomes and various ‘biodiversity hotspots’ represented by study sites of 1 km^2 in size (biodiversity observatories). The northern part of the study region is characterised by subtropical summer rainfall while the southern part is dominated by winter rainfall, each with a range from 50 to 500 mm mean annual precipitation. Each observatory is subdivided into 100 ha plots and sampled by a stratified random selection of 25 profiles. Background and context of this central transdisciplinary sampling scheme are introduced and discussed.

The database of this study comprises 560 comprehensively analysed soil profiles classified according to the World Reference Base for Soil Resources. A strong overall variety in this data set is highlighted by the occurrence of 11 out of 30 possible reference groups (in WRB 1998, 32 in WRB 2006 respectively) from this globally recognised reference system. According to their dominance, two major groups can be distinguished: i) Arenosols, Leptosols, Regosols, Cambisols, and Calcisol recorded with 15 – 20 % each and ii) the group of Durisols, Luvisols, Podzols, Solonchak, Fluvisol and Gypsysols recorded with only < 5 % each. The 22 analysed observatories are each described by means of a regional introduction followed by detailed soil analyses of the observatory including main reference profiles and a comprehensive discussion of soil property variability and ecological importance. By comparative analyses of soil and vegetation patterns, various impacts of the main ecological drivers along the transect are evident. The driving key factor in these water-controlled ecosystems is the soil water supply. Next to overall precipitation, this is mainly driven by soil parent material and soil texture, but also to some extent by osmotic effects of salt accumulations, surface sealing and other parameters. Nutrients and biotic impacts due to termite activity also play a major role along the transect. It can be stated that the variability of soil properties in the studied drylands is high for both, the overall transect and within the observatories. Looking at the different scales of soil patterns along the transect, distinct differences are evident. Whereas in the northern part of the transect main changes occur on mean distances of 100 – 300 m and are primarily substrate-driven, the southern part of the transect additionally shows small-scale structured variations in soils and soil properties (1 – 100 m).

The pedodiversity analyses started with an extensive literature review on diversity analysis techniques and the current status of pedodiversity research. Subsequently, this study's soil database was used for three different approaches to derive pedodiversity indices: i) Taxonomic pedodiversity using soil units (WRB), ii) Parametric classification as a newly developed, strictly parameter-based classification with 'soil-eco-types', and iii) Parametric space pedodiversity by means of directly using parametric values for the creation of '*environmental envelopes*', likewise a novel approach using convex hull algorithms. The methodological development of the approaches is a central part of this thesis and comprises an extensive discussion of the advantages, disadvantages and preconditions of the different calculation methods. For the taxonomic pedodiversity, the applicability of the WRB on the applied scale of 1 km² was tested and revealed a relatively high sensitivity of the system. Concerning the parametric approaches, a pre-selection of ecological important parameters is discussed and a classification system for soil-eco-types was tested in five different variants of class systems in order to identify the optimum sensitivity. The parametric space approach also focuses on integrative ecologically important parameters namely pH-value, electrical conductivity EC, organic carbon OC, soil texture, and available rooting space. These parameters were used to construct environmental envelopes with convex hull algorithms up to

5 dimensions resulting in an overall measure for abiotic heterogeneity of a single observatory. All approaches reveal comparable overall trends of pedodiversity along the transect with highest values in the Namaqualand observatories. Next to the important local influences of important soil parameters, a significant influence of climate regime, rainfall amount as well as soil parent material is detectable. In order to gain insight into the local spatial behaviour of soils, soil inventories were used to construct soil-area-curves providing insights into the relation of soil variability and included area. Correlation analyses with phytodiversity data of the BIOTA project show a general correspondence with highest r-squares of 0.9 indicating a strong relationship between pedo- and biodiversity for the studied area.

The methodology applied in this thesis using standardised soil surveys with subsequent ecological interpretation of the individual observatories managed to contribute considerably to the knowledge about soil spatial patterns and soil properties in the study region. It revealed specific regional trends regarding soil properties as well as observatory specific information about the spatial scale of changes in soil properties and the main ecological drivers behind these patterns. Pedodiversity analyses showed that the sensitivity of the different approaches has to be considered carefully with respect to the research question. Furthermore, the study was able to show that parameter based pedodiversity methods are more precise for ecological characterisation. Correlated to phytodiversity data, the novel approach ‘Parametric space’ pedodiversity shows highest r-square values explaining up to 90 % of the species richness of higher plants. The results show that besides the geostatisticial description of single parameter values, pedodiversity indices provide an integrative measure for soil variation of defined areas and that the convex hull method provides a powerful tool for creating a diversity measure which is neither affected by class size and limits nor by autocorrelation patterns. The study showed how taxonomic distances are effectively captured and quantified by the use of convex hull algorithms and that advanced pedodiversity analyses may provide important future tools for a quantitative pedosphere characterisation.

9 Zusammenfassung

Böden stehen als zentraler Bestandteil in der Schnittstelle von Atmosphäre, Lithosphäre, Biosphäre und Hydrosphäre und spiegeln auf integrative Weise die unterschiedlichen Einflüsse dieser Sphären wider. Der Boden ist eine der wichtigsten Ressourcen für die belebte Umwelt und daher ein wichtiger Faktor für die Biodiversität. Neben dem Einfluss von Landnutzung und Wechselwirkungen innerhalb von Lebensgemeinschaften werden Böden und Bodenvariabilität auf der lokalen und regionalen Ebene als eine der Haupteinflussgrößen für Artenreichtum betrachtet, aber integrierende Quantifizierungen zur Diversität von Böden vergleichbar den Indices in der Biodiversität sind bisher nur eingeschränkt möglich. Pedodiversität steht als Begriff für eine Quantifizierung von Bodenvariabilität und kann als integrierender Index für Bodeninformation innerhalb eines betrachteten Raumes genutzt werden. Pedodiversität wird abhängig von Fragestellung und Kontext, unter taxonomischen, genetischen, parametrischen oder funktionalen Aspekten betrachtet. Quantitative Analysen von Pedodiversität können einen wichtigen Beitrag zum funktionellen Verständnis von Ökosystemen leisten.

In dieser Arbeit wurde die Pedodiversität ausgewählter Untersuchungsareale in den Trockengebieten des südlichen Afrikas untersucht. Schwerpunkt der Untersuchungen war die Erfassung und Quantifizierung der Pedodiversität, sowie deren Bedeutung für die Ökosysteme. Eines der Hauptziele war hierbei die Erfassung der Böden, ihrer Eigenschaften und Musterbildungen auf zwei Betrachtungsniveaus: a) auf lokaler Ebene auf Testflächen von 1 km^2 Größe (Biodiversitätsobservatorien) in verschiedenen Biomen und b) unter Nutzung der lokalen Ergebnisse von 22 Observatorien auf einer subkontinentalen Ebene entlang eines Transekts von Nordnamibia bis zur Kaphalbinsel in Südafrika über 2500 km Länge. Das zweite Hauptziel der Arbeit ist die Entwicklung verschiedener Methoden zur Quantifizierung der Pedodiversität auf den Untersuchungsflächen und deren Vergleich im Transektverlauf. Aufbauend auf diesen Ergebnissen werden die Beziehungen zur Phytodiversität des Untersuchungsraumes geprüft und diskutiert.

Die Arbeit ist im Rahmen des interdisziplinären Forschungsprojektes BIOTA Southern Africa entstanden, welches die Biodiversität unter dem Einfluss von Landnutzung und Klimawandel untersucht (www.biota-africa.org). Der aride bis semi-aride Untersuchungsraum umfasst alle wesentlichen Biome Namibias und des westlichen Südafrikas bis in die Kapregion und enthält einige ‚biodiversity hotspots' die sich durch ihren Reichtum an Endemiten auszeichnen. Entlang des Transekts wurden auf 22 Observatorien von 100 ha Größe Bodenuntersuchungen mit jeweils 25 Profilen durchgeführt. Die Auswahl der Beprobungsprofile erfolgte mittels einer speziell angepassten stratifizierten Zufallsbeprobung. Der Hintergrund und die Entwicklung dieses Verfahrens werden erläutert.

Die Auswertungen beruhen auf 560 umfassend analysierten und nach World Reference Base for Soil Resources klassifizierten Profilen. Die Böden umfassen ein weites Spektrum von 11 aus insgesamt 30 weltweit möglichen „Reference groups“ (nach WRB 1998; 32 groups nach WRB 2006). Hinsichtlich der Frequenz des Auftretens können zwei Hauptgruppen unterschieden werden: a) Arenosols, Leptosols, Regosols, Cambisols, und Calcisols mit jeweils 15 – 20 % und b) Durisols, Luvisols, Podzols, Solonchak, Fluvisol und Gypsysols mit einer Häufigkeit von jeweils < 5 % in der Gesamtdatenbasis. Jedes der 22 untersuchten Observatorien wird hinsichtlich der regionalen Umweltbedingungen sowie der bodenkundlichen Situation ausführlich beschrieben. Dies umfasst Leitprofile, Bodeninventarkarten sowie eine umfassende Diskussion der analysierten Bodenvariabilität und deren ökologische Bedeutung. Durch vergleichende Analysen der Boden- und Vegetationsmuster konnten die Haupteinflussfaktoren der Böden entlang des Transekts herausgestellt werden. Als dominanter, die Vegetationsmuster steuernder Faktor ist das verfügbare Bodenwasser zu nennen. Neben der Menge des primären Niederschlags differenziert im wesentlichen das Ausgangsmaterial und die Textur das Wasserangebot, zudem sind partiell aber auch osmotische Effekte durch Salzbelastung sowie Oberflächenverkrustungen als wirksam zu benennen. Des Weiteren sind Musterbildungen durch Nährstoffunterschiede sowie insbesondere ein starker biotischer Einfluss auf Böden und Vegetation durch Termiten zu beobachten. Die Variabilität der Bodeneigenschaften im Untersuchungsgebiet ist vergleichsweise hoch, sowohl innerhalb der einzelnen Observatorien als auch in der Betrachtung des Gesamttransekts. Neben den Einflüssen durch Termiten sind Skalenunterschiede in der Musterbildung entlang des Transektverlaufs bedeutsam. Während in den nördlichen, von Sommerregen dominierten Observatorien signifikante Wechsel von Bodeneinheiten im Abstand von 100-300 m auftreten und im Wesentlichen durch Substratwechsel bedingt sind, finden sich zusätzlich kleinräumige Wechsel im Abstand von 1 m -100 m im ariden Bereich des südlichen Transektabschnitts.

Aufbauend auf einer intensiven Literaturrecherche zu Methoden der Diversitätsmessung und einer Analyse der bereits bestehenden Techniken zur Beschreibung von Pedodioversität wurden 3 verschiedene Methoden angewendet bzw. neu entwickelt. 1) Taxonomische Pedodiversität durch Nutzung der klassierten Bodeneinheiten nach World Reference Base (WRB), 2) Parametrische Pedodiversität als ein neu entwickeltes, rein parametrisch basiertes Klassifikationsverfahren mit so genannten ‘Soil-eco-types’ und 3) Parametrische Merkmalsraumdiversität als ein in dieser Arbeit neu entwickeltes Verfahren durch die Nutzung ökologisch relevanter Parameter zur Berechnung eines abiotischen Merkmalsraumes (*‘environmental envelopes’*). Diese Berechnung erfolgt durch die Anwendung des mathematischen Verfahrens der konvexen Hülle in mehreren Dimensionen. Die methodische Entwicklung der Verfahren ist ein zentraler Teil dieser Arbeit und umfasst auch eine ausführliche Diskussion der Vor- und Nachteile sowie der Vorraussetzungen der jeweiligen Methode.

Für das Verfahren der taxonomischen Pedodiversität wurde die Eignung der WRB hinsichtlich ihrer Differenzierungsfähigkeit auf der Skala von 1 km^2 geprüft. Für die Verfahren der parametrisch basierten Pedodiversität wird eine Auswahl der ökologisch relevanten Parameter diskutiert. Fünf verschiedene Varianten (Klassengrößen und Grenzen) zur Bildung von ‚Soil-eco-types’ wurden getestet um eine geeignete Sensitivität zu bestimmen. Die Methode des parametrischen Merkmalsraumes fußt ebenfalls auf der Kombination der ökologisch relevanten Parameter pH, elektrische Leitfähigkeit, organischer Kohlenstoff, Textur und Wurzelraum. Im Vergleich zu Klassierungsverfahren werden die Parameter hier nach Normalisierung kombiniert in einem mehrdimensionalen Raum dargestellt und das Volumens ihrer konvexen Hülle bestimmt. Dieses Maß dient als Kennzeichnung der abiotischen Heterogenität der betrachteten Fläche. Alle angewendeten Verfahren zeigten ähnliche Trends hinsichtlich der Ergebnisse im Transektverlauf mit den Maximalwerten im Bereich des Namaqualandes. Neben den lokalen Differenzierungen relevanter Bodenparameter sind auch klimatische Einflüsse wie Art und Menge des Regenfalls sowie die Art des Ausgangsmaterials in den Trends zu erkennen. Für die Beurteilung der lokalen räumlichen Anordnung des Bodeninventars wurden ‚Boden-Areal-Kurven' erstellt und hinsichtlich ihrer Aussagekraft interpretiert. Korrelationsanalysen mit Phytodiversitätdaten zeigen enge Beziehungen zwischen Pedo- und Biodiversität für den Untersuchungsraum.

Die in dieser Arbeit angewendete Methode der standardisierten Erfassung von Böden definierter Untersuchungsräume und ihrer ökologischen Interpretation konnte in erheblichem Maße zu dem Wissen über Bodenmuster und Bodeneigenschaften des Untersuchungsraumes beitragen. Es konnten sowohl regionale Trends der Bodeneigenschaften als auch auf die Observatorien bezogene Information zur Musterbildung und der ökologischen Bedeutung und Ursachen gezeigt werden. Die Weiterentwicklung und Auswertungen zur Quantifizierung der Pedodiversität haben gezeigt, dass das Verhalten und die Sensitivität des jeweiligen Verfahrens bei der Anwendung berücksichtigt bzw. angepasst werden sollte. Im Kontext dieser Arbeit sind die parametrisch basierten Verfahren besser in der Lage die tatsächlichen ökologischen Gegebenheiten zu integrieren. In Korrelation zur Phytodiversität konnte der neu entwickelt Ansatz Parametrischer Merkmalsraum bis zu 90 % des Artenreichtums der höheren Pflanzen ausdrücken.

Die Ergebnisse der Arbeit zeigen, dass neben der räumlich expliziten Beschreibung einzelner Bodenparameter durch geostatistische Verfahren, die Quantifizierung von Pedodiversität eine integrierende Möglichkeit zur Beschreibung von Bodenheterogenität definierter Flächen bietet. Insbesondere die Anwendung konvexer Hüllen ist ein geeignetes Werkzeug, da dieses Verfahren weder durch Klassengröße und -grenzen noch durch Autokorrelationen einzelner Parameter beeinflussbar ist. Es konnte gezeigt werden, dass taxonomische Distanzen durch den Merkmalsraum quantifiziert werden und dass die Weiterentwicklung dieser Verfahren einen wichtigen Beitrag zur qualitativen und quantitativen Charakterisierung der Pedosphäre und ihrer Beziehung zur Biodiversität leisten kann.

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12 Appendices

Due to the large amount of data it is not possible to provide the single basic data in printed form. All data used in this thesis is provided on the attached CD-Rom or can be requested via email (a.petersen@ifb.uni-hamburg.de). The appendices are structured as follows:

I. List of soil units printed
II. Abbreviation sheet for data files printed
III. Soil data A (profile data) on CD (filename Appendix_III_profile_data)
IV. Soil data B (horizon data) on CD (filename Appendix_IV_horizon_data)
V. Illustration of the ranking procedure
VI. Access scheme for online data (photos, maps, graphs)

Appendix VI refers to several soil information including graphs and pictures are available online via the BIOTA website:

i) Variability graphs of selected soil properties in three depth intervals for the entire observatory

ii) Profile and site photographs for each profile

iii) Graphs of selected soil properties for each profile

Data access is possible via www.biota-africa.org

→ disciplines

→ soil science

→ select an observatory

→ single profile access as explained below

Appendix I List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
489	01 Mile 46	00	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
133	01 Mile 46	02	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
490	01 Mile 46	03	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
491	01 Mile 46	05	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
485	01 Mile 46	09	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
492	01 Mile 46	14	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
484	01 Mile 46	18	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
134	01 Mile 46	22	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
494	01 Mile 46	23	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
493	01 Mile 46	25	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
483	01 Mile 46	39	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
132	01 Mile 46	42	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
131	01 Mile 46	52	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
495	01 Mile 46	53	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
488	01 Mile 46	60	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
130	01 Mile 46	72	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
487	01 Mile 46	77	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
486	01 Mile 46	87	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
129	01 Mile 46	92	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
116	02 Mutompo	04	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
113	02 Mutompo	06	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
115	02 Mutompo	14	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
114	02 Mutompo	15	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
112	02 Mutompo	17	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
110	02 Mutompo	24	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
482	02 Mutompo	32	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
109	02 Mutompo	34	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
111	02 Mutompo	41	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
97	02 Mutompo	42	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
108	02 Mutompo	44	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
480	02 Mutompo	47	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
98	02 Mutompo	52	Dystric - Stagnic Regosol	Stagnic Regosol (Dystric)
107	02 Mutompo	54	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
106	02 Mutompo	55	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
104	02 Mutompo	59	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
481	02 Mutompo	63	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
105	02 Mutompo	64	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric, Greyic)
102	02 Mutompo	74	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
103	02 Mutompo	76	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
101	02 Mutompo	84	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
479	02 Mutompo	89	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
99	02 Mutompo	93	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric, Greyic)
100	02 Mutompo	94	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
127	03 Sonop	01	Rubic - Ferralic Arenosol (Dystric)	Ferralic Rubic Arenosol (Dystric)
126	03 Sonop	21	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
125	03 Sonop	31	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
119	03 Sonop	41	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
118	03 Sonop	51	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
117	03 Sonop	61	Eutric - Stagnic Regosol	Stagnic Regosol (Eutric, Endoclayic)
120	03 Sonop	71	Haplic Calcisol	Haplic Calcisol
121	03 Sonop	81	Haplic Calcisol	Haplic Calcisol
122	03 Sonop	91	Eutric Cambisol	Haplic Cambisol (Eutric)
123	03 Sonop	t	Eutric Cambisol	Haplic Cambisol (Eutric)
124	03 Sonop	t	Eutric - Ferralic Arenosol	Ferralic Arenosol (Eutric)
128	03 Sonop	t	Rubic - Ferralic Arenosol (Dystric)	Ferralic Rubic Arenosol (Dystric)
47	04 Toggekry 250	05	Eutric - Endoskeletic Cambisol	Haplic Cambisol (Eutric, Endoskeletic)
46	04 Toggekry 250	06	Dystric - Ferralic Cambisol	Ferralic Cambisol (Dystric)
52	04 Toggekry 250	08	Chromic Luvisol	Haplic Luvisol (Chromic)
50	04 Toggekry 250	15	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
45	04 Toggekry 250	17	Eutric - Chromic Cambisol	Haplic Cambisol (Eutric, Chromic)
44	04 Toggekry 250	18	Chromic Luvisol	Haplic Luvisol (Clayic, Chromic)
33	04 Toggekry 250	21	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
61	04 Toggekry 250	22	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
60	04 Toggekry 250	23	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
49	04 Toggekry 250	28	Chromic Luvisol	Haplic Luvisol (Chromic)
30	04 Toggekry 250	30	Chromic - Arenic Luvisol	Haplic Luvisol (Arenic, Chromic)
31	04 Toggekry 250	31	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
62	04 Toggekry 250	32	Ferralic - Hypoluvic Arenosol (Hyperdystric)	Ferralic Hypoluvic Arenosol (Hyperdystric)
51	04 Toggekry 250	35	Hypereutric Cambisol	Haplic Cambisol (Hypereutric, Epiclayic)
43	04 Toggekry 250	38	Eutric - Chromic Cambisol	Haplic Cambisol (Eutric, Clayic, Chromic)
32	04 Toggekry 250	41	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
63	04 Toggekry 250	42	Dystric - Ferralic Arenosol	Ferralic Arenosol (Dystric)
34	04 Toggekry 250	44	Dystric - Ferralic Cambisol	Ferralic Cambisol (Dystric)
35	04 Toggekry 250	45	Dystric Cambisol	Haplic Cambisol (Dystric)
48	04 Toggekry 250	48	Haplic Luvisol	Haplic Luvisol (Endoclayic)
64	04 Toggekry 250	50	Chromic Luvisol	Haplic Luvisol (Chromic)

Appendix I List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
42	04 Toggekry 250	58	Eutric - Chromic Cambisol	Haplic Cambisol (Eutric, Endoclayic, Chromic)
58	04 Toggekry 250	65	Eutric Cambisol	Haplic Cambisol (Eutric)
28	04 Toggekry 250	71	Dystric Cambisol	Haplic Cambisol (Dystric)
36	04 Toggekry 250	73	Dystric - Endoskeletic Cambisol	Haplic Cambisol (Dystric, Endoskeletic)
57	04 Toggekry 250	76	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
41	04 Toggekry 250	78	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
53	04 Toggekry 250	79	Dystric - Chromic Cambisol	Haplic Cambisol (Dystric, Chromic)
29	04 Toggekry 250	82	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
59	04 Toggekry 250	85	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
56	04 Toggekry 250	87	Haplic Luvisol	Haplic Luvisol (Clayic)
54	04 Toggekry 250	88	Haplic Luvisol	Haplic Luvisol
40	04 Toggekry 250	89	Dystric - Chromic Luvisol	Haplic Luvisol (Dystric, Endoclayic, Chromic)
27	04 Toggekry 250	90	Eutric Cambisol	Haplic Cambisol (Eutric)
65	04 Toggekry 250	91	Dystric - Ferralic Cambisol	Ferralic Cambisol (Dystric)
66	04 Toggekry 250	93	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
37	04 Toggekry 250	95	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
38	04 Toggekry 250	96	Ferralic - Hypoluvic Arenosol (Dystric)	Ferralic Hypoluvic Arenosol (Dystric)
55	04 Toggekry 250	97	Hypereutric - Chromic Cambisol	Haplic Cambisol (Hypereutric, Chromic)
39	04 Toggekry 250	98	Chromic Luvisol	Haplic Luvisol (Endoclayic, Chromic)
1	05 Otjiamongombe	03	Chromic Luvisol	Haplic Luvisol (Chromic)
3	05 Otjiamongombe	11	Skeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Skeletic)
25	05 Otjiamongombe	12	Epipetric Calcisol	Epipetric Calcisol
23	05 Otjiamongombe	20	Eutric Cambisol	Haplic Cambisol (Eutric)
24	05 Otjiamongombe	21	Epipetric Calcisol	Epipetric Calcisol
15	05 Otjiamongombe	26	Haplic Luvisol	Haplic Luvisol (Endoclayic)
4	05 Otjiamongombe	32	Hypercalcic - Endopetric Calcisol	Hypercalcic Endopetric Calcisol
16	05 Otjiamongombe	36	Haplic Luvisol	Haplic Luvisol
11	05 Otjiamongombe	44	Haplic Luvisol	Haplic Luvisol (Clayic)
17	05 Otjiamongombe	46	Haplic Luvisol	Haplic Luvisol (Endoclayic)
19	05 Otjiamongombe	48	Chromic Luvisol	Haplic Luvisol (Chromic)
18	05 Otjiamongombe	49	Haplic Luvisol	Haplic Luvisol
22	05 Otjiamongombe	52	Eutric Cambisol	Haplic Cambisol (Eutric, Clayic)
5	05 Otjiamongombe	54	Calcic Luvisol	Calcic Luvisol
12	05 Otjiamongombe	61	Endopetric Calcisol	Endopetric Calcisol
20	05 Otjiamongombe	68	Chromic Luvisol	Haplic Luvisol (Chromic, Endoclayic)
21	05 Otjiamongombe	69	Chromic Luvisol	Haplic Luvisol (Chromic)
13	05 Otjiamongombe	72	Eutric Cambisol	Haplic Cambisol (Eutric, Endoclayic)
6	05 Otjiamongombe	77	Haplic Luvisol	Haplic Luvisol
8	05 Otjiamongombe	81	Hypercalcic - Endopetric Calcisol	Hypercalcic Endopetric Calcisol
26	05 Otjiamongombe	82	Epipetric Calcisol	Epipetric Calcisol (Epiclayic)
9	05 Otjiamongombe	83	Hypercalcic Calcisol	Haplic Calcisol (Endosiltic)
10	05 Otjiamongombe	85	Hypercalcic Calcisol	Hypercalcic Calcisol
7	05 Otjiamongombe	91	Endopetric Calcisol	Endopetric Calcisol
14	05 Otjiamongombe	98	Haplic Luvisol	Haplic Luvisol
670	06 Okamboro	04	Endoskeletic - Arenic Regosol (Hypereutric)	Haplic Regosol (Hypereutric, Endoskeletic, Arenic)
671	06 Okamboro	07	Eutric - Endoleptic Cambisol	Endoleptic Cambisol (Eutric)
669	06 Okamboro	13	Arenic - Endoleptic Regosol (Episkeletic Eutric)	Endoleptic Regosol (Eutric, Episkeletic, Arenic)
667	06 Okamboro	14	Endoskeletic - Arenic Regosol (Eutric)	Haplic Regosol (Eutric, Endoskeletic, Arenic)
668	06 Okamboro	24	Endoskeletic - Arenic Regosol (Eutric)	Haplic Regosol (Eutric, Endoskeletic, Arenic)
672	06 Okamboro	26	Arenic - Endoleptic Regosol (Episkeletic Hypereutric)	Endoleptic Regosol (Hypereutric, Episkeletic, Arenic)
673	06 Okamboro	28	Calcaric - Endoleptic Regosol (Episkeletic Hypereutric)	Endoleptic Regosol (Calcaric, Hypereutric, Episkeletic)
666	06 Okamboro	34	Episkeletic - Arenic Regosol (Eutric)	Haplic Regosol (Eutric, Episkeletic, Arenic)
674	06 Okamboro	38	Arenic - Endoleptic Regosol (Episkeletic Hypereutric)	Endoleptic Regosol (Hypereutric, Episkeletic, Arenic)
693	06 Okamboro	40	Calcaric - Arenic Regosol (Episkeletic Hypereutric)	Haplic Regosol (Calcaric, Hypereutric, Episkeletic, Arenic)
686	06 Okamboro	43	Calcaric - Arenic Regosol (Hypereutric)	Haplic Regosol (Calcaric, Hypereutric, Arenic)
676	06 Okamboro	48	Arenic - Endoleptic Regosol (Episkeletic Hypereutric)	Epileptic Regosol (Hypereutric, Episkeletic, Arenic)
677	06 Okamboro	49	Arenic - Epileptic Regosol (Episkeletic Eutric)	Epileptic Regosol (Eutric, Episkeletic, Arenic)
690	06 Okamboro	51	Endoskeletic - Calcaric Regosol (Hypereutric)	Haplic Regosol (Calcaric, Hypereutric, Endoskeletic)
679	06 Okamboro	59	Arenic - Endoleptic Regosol (Episkeletic Hypereutric)	Endoleptic Regosol (Hypereutric, Episkeletic, Arenic)
688	06 Okamboro	63	Episkeletic - Endoleptic Regosol (Hypereutric)	Endoleptic Regosol (Hypereutric, Episkeletic)
678	06 Okamboro	65	Calcaric - Arenic Regosol (Hypereutric)	Haplic Regosol (Calcaric, Hypereutric, Arenic)
680	06 Okamboro	66	Endopetric Calcisol	Endopetric Calcisol
675	06 Okamboro	69	Arenic - Endoleptic Regosol (Episkeletic Hypereutric)	Epileptic Regosol (Hypereutric, Episkeletic, Arenic)
681	06 Okamboro	79	Endoskeletic - Arenic Regosol (Eutric)	Regosol (Eutric, Endoskeletic, Arenic)
691	06 Okamboro	80	Arenic - Epileptic Regosol (Eutric)	Epileptic Regosol (Eutric, Arenic)
687	06 Okamboro	83	Endoskeletic - Arenic Regosol (Hypereutric)	Haplic Regosol (Hypereutric, Endoskeletic, Arenic)
682	06 Okamboro	86	Arenic - Epileptic Regosol (Calcaric Hypereutric)	Epileptic Regosol (Calcaric, Hypereutric, Arenic)
685	06 Okamboro	88	Calcaric - Endoleptic Cambisol (Episkeletic Hypereutric)	Endoleptic Cambisol (Calcaric, Hypereutric, Episkeletic)
683	06 Okamboro	89	Arenic - Endoleptic Regosol (Episkeletic Hypereutric)	Endoleptic Regosol (Hypereutric, Episkeletic, Arenic)
689	06 Okamboro	93	Arenic - Endoleptic Regosol (Hypereutric)	Endoleptic Regosol (Hypereutric, Episkeletic, Arenic)
684	06 Okamboro	97	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
502	10 Gellap Ost 3	00	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
501	10 Gellap Ost 3	01	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
74	10 Gellap Ost 3	05	Aridic - Epileptic Regosol (Episkeletic Hypereutric)	Epileptic Regosol (Hypereutric, Aridic, Episkeletic, Siltic)
67	10 Gellap Ost 3	09	Eutric - Aridic Leptosol	Haplic Leptosol (Eutric, Aridic)
75	10 Gellap Ost 3	13	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)

Appendix I

List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
510	10 Gellap Ost 3	17	Skeletic - Epileptic Regosol (Hypereutric)	Epileptic Regosol (Hypereutric, Skeletic)
68	10 Gellap Ost 3	19	Aridic - Epileptic Regosol (Episkeletic Eutric)	Epileptic Regosol (Eutric, Aridic, Episkeletic, Siltic)
81	10 Gellap Ost 3	21	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
70	10 Gellap Ost 3	28	Skeletic - Epileptic Regosol (Hypereutric)	Epileptic Regosol (Hypereutric, Skeletic, Siltic)
514	10 Gellap Ost 3	43	Skeletic - Epileptic Regosol (Hypereutric)	Epileptic Regosol (Hypereutric, Skeletic)
73	10 Gellap Ost 3	46	Aridic - Epileptic Regosol (Episkeletic Hypereutric)	Epileptic Regosol (Hypereutric, Aridic, Episkeletic)
69	10 Gellap Ost 3	49	Aridic - Epileptic Regosol (Eutric)	Epileptic Regosol (Eutric, Aridic, Siltic)
80	10 Gellap Ost 3	60	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
78	10 Gellap Ost 3	62	Eutric - Aridic Regosol	Haplic Regosol (Eutric, Aridic)
513	10 Gellap Ost 3	63	Skeletic - Aridic Regosol (Hypereutric)	Haplic Regosol (Hypereutric, Aridic, Skeletic)
72	10 Gellap Ost 3	66	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
77	10 Gellap Ost 3	72	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
512	10 Gellap Ost 3	73	Eutric - Aridic Leptosol	Haplic Leptosol (Eutric, Aridic)
79	10 Gellap Ost 3	80	Aridic - Arenic Fluvisol (Eutric)	Haplic Fluvisol (Eutric, Aridic, Arenic)
511	10 Gellap Ost 3	82	Skeletic - Aridic Regosol (Hypereutric)	Haplic Regosol (Hypereutric, Aridic, Skeletic)
76	10 Gellap Ost 3	92	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
71	10 Gellap Ost 3	99	Aridic - Epileptic Cambisol (Episkeletic Hypereutric)	Epileptic Cambisol (Hypereutric, Episkeletic, Aridic, Clayic)
87	11 Nabaos 7	01	Aridic - Endoleptic Regosol (Episkeletic Hypereutric)	Endoleptic Regosol (Hypereutric, Aridic, Siltic)
505	11 Nabaos 7	08	Aridic - Lithic Leptosol (Hypereutric)	Lithic Leptosol (Hypereutric, Aridic)
96	11 Nabaos 7	09	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
86	11 Nabaos 7	11	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
94	11 Nabaos 7	17	Endoleptic - Arenic Regosol (Aridic Hypereutric)	Endoleptic Regosol (Hypereutric, Aridic, Arenic)
95	11 Nabaos 7	19	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
507	11 Nabaos 7	23	Skeletic - Aridic Regosol (Hypereutric)	Haplic Regosol (Hypereutric, Aridic, Skeletic)
506	11 Nabaos 7	25	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
84	11 Nabaos 7	30	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
85	11 Nabaos 7	31	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
93	11 Nabaos 7	37	Hyperskeletic - Aridic Leptosol (Hypereutric)	Haplic Leptosol (Hypereutric, Aridic, Hyperskeletic, Siltic)
92	11 Nabaos 7	45	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
91	11 Nabaos 7	53	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic, Endoclayic)
90	11 Nabaos 7	57	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
89	11 Nabaos 7	59	Aridic - Paralithic Leptosol (Hypereutric)	Paralithic Leptosol (Hypereutric, Aridic)
83	11 Nabaos 7	77	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
509	11 Nabaos 7	79	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
88	11 Nabaos 7	89	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
82	11 Nabaos 7	94	Episkeletic - Aridic Regosol (Hypereutric)	Haplic Regosol (Hypereutric, Episkeletic, Aridic, Clayic)
508	11 Nabaos 7	97	Hypereutric - Aridic Regosol	Haplic Regosol (Hypereutric, Aridic)
503	11 Nabaos 7	98	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
504	11 Nabaos 7	99	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
545	16 Wlotzkasbaken	06	Gypsiric - Aridic Leptosol (Calcaric Hypereutric)	Haplic Leptosol (Gypsiric, Calcaric, Hypereutric, Aridic)
500	16 Wlotzkasbaken	13	Aridic - Epileptic Gypsisol	Gypsic Hypersalic Solonchak (Aridic)
546	16 Wlotzkasbaken	16	Aridic - Epileptic Gypsisol	Gypsic Hypersalic Solonchak (Aridic)
537	16 Wlotzkasbaken	22	Aridic - Lithic Leptosol (Calcaric Hypereutric)	Lithic Leptosol (Calcaric, Hypereutric, Aridic)
548	16 Wlotzkasbaken	35	Aridic - Epileptic Gypsisol	Gypsic Hypersalic Solonchak (Aridic)
547	16 Wlotzkasbaken	36	Aridic - Lithic Leptosol (Gypsiric Calcaric)	Lithic Leptosol (Gypsiric, Calcaric, Aridic)
550	16 Wlotzkasbaken	39	Gypsiric - Aridic Leptosol (Calcaric Hypereutric)	Haplic Leptosol (Gypsiric, Calcaric, Hypereutric, Aridic)
549	16 Wlotzkasbaken	40	Gypsiric - Aridic Leptosol (Calcaric Hypereutric)	Haplic Leptosol (Gypsiric, Calcaric, Hypereutric, Aridic)
539	16 Wlotzkasbaken	40	Aridic - Epileptic Gypsisol	Gypsic Hypersalic Solonchak (Aridic)
538	16 Wlotzkasbaken	42	Aridic - Lithic Leptosol (Calcaric Hypereutric)	Lithic Leptosol (Calcaric, Hypereutric, Aridic)
555	16 Wlotzkasbaken	57	Aridic - Epileptic Gypsisol	Epileptic Gypsisol (Aridic, Siltic)
551	16 Wlotzkasbaken	69	Gypsiric - Aridic Leptosol (Hypereutric)	Hypersalic Solonchak (Aridic)
540	16 Wlotzkasbaken	70	Aridic - Epileptic Gypsisol	Gypsic Hypersalic Solonchak (Aridic)
544	16 Wlotzkasbaken	72	Aridic - Lithic Leptosol (Gypsiric Calcaric)	Lithic Leptosol (Gypsiric, Calcaric, Aridic)
556	16 Wlotzkasbaken	73	Aridic - Lithic Leptosol (Gypsiric Calcaric)	Lithic Leptosol (Gypsiric, Calcaric, Aridic)
543	16 Wlotzkasbaken	82	Aridic - Epileptic Gypsisol	Epileptic Gypsisol (Aridic)
553	16 Wlotzkasbaken	86	Aridic - Lithic Leptosol (Calcaric Hypereutric)	Lithic Leptosol (Calcaric, Hypereutric, Aridic)
541	16 Wlotzkasbaken	91	Calcaric - Aridic Leptosol (Hypereutric)	Haplic Leptosol (Calcaric, Hypereutric, Aridic)
542	16 Wlotzkasbaken	92	Calcaric - Aridic Leptosol (Hypereutric)	Haplic Leptosol (Calcaric, Hypereutric, Aridic)
552	16 Wlotzkasbaken	95	Hypereutric - Aridic Leptosol	Hypersalic Solonchak (Aridic)
155	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
156	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
157	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
158	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
159	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
160	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
161	17 Alpha	t	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
162	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
139	17 Alpha	t		
163	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
164	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
165	17 Alpha	t	Rubic - Ferralic Arenosol (Dystric)	Ferralic Rubic Arenosol (Dystric)
166	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
167	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
168	17 Alpha	t	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
175	17 Alpha	01	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
178	17 Alpha	04	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)

Appendix I List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
140	17 Alpha	07	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
174	17 Alpha	11	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
176	17 Alpha	12	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
177	17 Alpha	13	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
143	17 Alpha	26	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
141	17 Alpha	28	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
144	17 Alpha	36	Hypercalcic - Petric Calcisol	Hypercalcic Petric Calcisol
142	17 Alpha	37	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
173	17 Alpha	40	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
171	17 Alpha	43	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
145	17 Alpha	48	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
172	17 Alpha	51	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
170	17 Alpha	53	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
146	17 Alpha	57	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
169	17 Alpha	63	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
147	17 Alpha	68	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
148	17 Alpha	78	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
154	17 Alpha	81	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
153	17 Alpha	83	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
152	17 Alpha	84	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
179	17 Alpha	90	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
151	17 Alpha	94	Rubic - Ferralic Arenosol (Hypereutric)	Ferralic Rubic Arenosol (Hypereutric)
150	17 Alpha	95	Hypercalcic - Petric Calcisol (Eutric)	Hypercalcic Petric Calcisol
149	17 Alpha	97	Rubic - Ferralic Arenosol (Eutric)	Ferralic Rubic Arenosol (Eutric)
515	18 Koeroegapvlakte	t	Hypocalcic - Endopetric Durisol	Hypocalcic Duric Hypersalic Solonchak
516	18 Koeroegapvlakte	t	Chromic - Aridic Durisol	Haplic Durisol (Aridic, Chromic)
517	18 Koeroegapvlakte	t	Hypocalcic Durisol	Hypocalcic Duric Hypersalic Solonchak
518	18 Koeroegapvlakte	t	Aridic - Endopetric Durisol	Endopetric Durisol (Aridic)
519	18 Koeroegapvlakte	t	Aridic - Epipetric Durisol (Chromic)	Epipetric Durisol (Aridic, Chromic)
520	18 Koeroegapvlakte	t		
521	18 Koeroegapvlakte	t		
430	18 Koeroegapvlakte	02	Hypersalic - Duric Solonchak (Ochric)	Duric Hypersalic Solonchak
433	18 Koeroegapvlakte	07	Chromic - Endopetric Durisol (Hypereutric)	Endopetric Durisol
434	18 Koeroegapvlakte	08	Hypocalcic - Epipetric Durisol (Chromic)	Hypocalcic Duric Hypersalic Solonchak
431	18 Koeroegapvlakte	20	Chromic - Epipetric Durisol (Hypereutric)	Epipetric Durisol (Chromic)
429	18 Koeroegapvlakte	22	Hypereutric - Chromic Cambisol	Haplic Cambisol (Hypereutric, Chromic)
449	18 Koeroegapvlakte	26	Aridic - Epipetric Durisol (Eutric)	Epipetric Durisol (Aridic, Siltic)
451	18 Koeroegapvlakte	31	Hypocalcic - Endopetric Durisol	Hypocalcic Endopetric Durisol
450	18 Koeroegapvlakte	34	Hypereutric - Arenic Fluvisol	Haplic Fluvisol (Hypereutric, Arenic)
428	18 Koeroegapvlakte	42	Hypocalcic - Endopetric Durisol (Hypereutric)	Hypocalcic Endopetric Durisol
438	18 Koeroegapvlakte	46	Aridic - Endopetric Durisol (Chromic Hypereutric)	Endopetric Durisol (Aridic)
435	18 Koeroegapvlakte	49	Chromic - Aridic Durisol (Hypereutric)	Haplic Durisol (Aridic, Chromic)
432	18 Koeroegapvlakte	50	Hypocalcic - Endopetric Durisol (Hypereutric)	Hypocalcic Endopetric Durisol
437	18 Koeroegapvlakte	56	Aridic - Endoleptic Cambisol (Hypereutric)	Endoleptic Cambisol (Hypereutric, Aridic)
436	18 Koeroegapvlakte	59	Chromic - Aridic Durisol (Hypereutric)	Haplic Durisol (Aridic, Chromic)
427	18 Koeroegapvlakte	62	Hypereutric - Arenic Fluvisol	Haplic Fluvisol (Hypereutric, Arenic)
452	18 Koeroegapvlakte	71	Aridic - Epipetric Durisol	Epipetric Durisol (Aridic)
447	18 Koeroegapvlakte	76	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
446	18 Koeroegapvlakte	78	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
426	18 Koeroegapvlakte	80	Aridic - Endopetric Durisol (Hypereutric)	Endopetric Durisol (Aridic)
445	18 Koeroegapvlakte	85	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
444	18 Koeroegapvlakte	86	Hypereutric - Aridic Cambisol	Haplic Cambisol (Hypereutric, Aridic)
448	18 Koeroegapvlakte	88	Aridic - Endopetric Durisol (Hypereutric)	Endopetric Durisol (Aridic)
413	18 Koeroegapvlakte	90	Hypereutric - Chromic Cambisol	Haplic Cambisol (Hypereutric, Chromic)
425	18 Koeroegapvlakte	91	Aridic - Endopetric Durisol (Hypereutric)	Endopetric Durisol (Aridic)
455	18 Koeroegapvlakte	92	Aridic - Endopetric Durisol	Endopetric Durisol (Aridic)
395	20 Numees	08	Skeletic - Endoleptic Calcisol	Calcic Solonchak
396	20 Numees	09	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
399	20 Numees	12	Aridic - Epileptic Regosol (Episkeletic Eutric)	Epileptic Regosol (Eutric, Aridic, Episkeletic)
423	20 Numees	17	Hypereutric - Aridic Leptosol	Haplic Leptosol (Hypereutric, Aridic)
400	20 Numees	22	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
401	20 Numees	23	Hypereutric - Aridic Leptosol	Haplic Leptosol (Hypereutric, Aridic)
403	20 Numees	25	Hypereutric Leptosol	HaplicLeptosol (Hypereutric)
394	20 Numees	28	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
464	20 Numees	30	Epipetric Durisol	Epipetric Durisol
402	20 Numees	34	Eutric Leptosol	Haplic Leptosol (Eutric)
391	20 Numees	36	Episkeletic - Epileptic Regosol (Hypereutric)	Epileptic Regosol (Hypereutric, Episkeletic)
390	20 Numees	47	Calcaric - Aridic Leptosol (Hypereutric)	Haplic Leptosol (Calcaric, Hypereutric, Aridic)
397	20 Numees	59	Hyposalic - Epileptic Regosol (Episkeletic)	Epileptic Regosol (Hyposalic, Episkeletic)
407	20 Numees	62	Aridic - Calcic Solonchak (Hypersalic)	Calcic Hypersalic Solonchak (Aridic)
393	20 Numees	66	Ochric - Hypersalic Solonchak	Hypersalic Solonchak
392	20 Numees	67	Episkeletic - Epipetric Calcisol	Calcic Hypersalic Solonchak
398	20 Numees	69	Hypereutric - Aridic Leptosol	Haplic Leptosol (Hypereutric, Aridic)
404	20 Numees	72	Aridic - Lithic Leptosol (Hypereutric)	Lithic Leptosol (Hypereutric, Aridic)
462	20 Numees	78	Skeletic Calcisol	Calcic Hypersalic Solonchak
405	20 Numees	81	Aridic - Epipetric Calcisol	Epipetric Calcisol (Aridic)
408	20 Numees	84	Arenic - Epileptic Regosol (Episkeletic Hypereutric)	Epileptic Regosol (Hypereutric, Episkeletic, Arenic)

Appendix I List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
461	20 Numees	87	Hyposalic - Aridic Regosol (Calcaric Episkeletic)	Hypersalic Solonchak (Aridic)
406	20 Numees	92	Aridic - Epipetric Calcisol (Episkeletic)	Calcic Hypersalic Solonchak (Aridic)
414	20 Numees	98	Skeletic - Epipetric Calcisol	Calcic Solonchak (Siltic)
409	20 Numees	99	Aridic - Arenic Regosol (Hyposalic Calcaric)	Hypersalic Solonchak (Aridic, Arenic)
529	21 Groot Derm 10	03	Ferralic - Aridic Arenosol (Hyposalic)	Ferralic Hyposalic Arenosol (Aridic)
415	21 Groot Derm 10	09	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Arenosol (Hypereutric, Aridic)
420	21 Groot Derm 10	21	Yermic - Epileptic Calcisol	Calcic Hypersalic Solonchak (Yermic)
418	21 Groot Derm 10	22	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Hyposalic Arenosol (Aridic)
528	21 Groot Derm 10	23	Ferralic - Aridic Arenosol (Hyposalic)	Ferralic Hyposalic Arenosol (Aridic)
530	21 Groot Derm 10	26	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Arenosol (Hypereutric, Aridic)
527	21 Groot Derm 10	30	Ferralic - Aridic Arenosol (Hyposalic)	Ferralic Hyposalic Arenosol (Aridic)
522	21 Groot Derm 10	39	Ferralic - Aridic Arenosol (Hyposalic)	Ferralic Hyposalic Arenosol (Aridic)
417	21 Groot Derm 10	52	Ferralic - Aridic Arenosol (Hypereutric)	Haplic Solonchak (Aridic, Arenic)
523	21 Groot Derm 10	67	Ferralic - Aridic Arenosol (Hyposalic)	Ferralic Hyposalic Arenosol (Aridic)
526	21 Groot Derm 10	72	Ferralic - Aridic Arenosol (Hyposalic)	Ferralic Hyposalic Arenosol (Aridic)
524	21 Groot Derm 10	76	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Arenosol (Hypereutric, Aridic)
416	21 Groot Derm 10	92	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Arenosol (Hypereutric, Aridic)
525	21 Groot Derm 10	98	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Arenosol (Hypereutric, Aridic)
419	21 Groot Derm 10	99	Ferralic - Aridic Arenosol (Hypereutric)	Ferralic Hyposalic Arenosol (Aridic)
209	22 Soebatsfontain	00	Calcaric - Mollic Cambisol (Episkeletic Hypereutric)	Haplic Cambisol (Calcaric, Hypereutric, Episkeletic)
180	22 Soebatsfontain	06	Arenic - Endoleptic Regosol (Dystric)	Endoleptic Regosol (Dystric, Arenic)
208	22 Soebatsfontain	11	Skeletic - Epileptic Regosol (Dystric)	Epileptic Regosol (Dystric, Skeletic)
181	22 Soebatsfontain	16	Eutric Leptosol	Haplic Leptosol (Eutric)
183	22 Soebatsfontain	19	Chromic - Arenic Durisol (Hypereutric)	Haplic Durisol (Arenic, Chromic)
207	22 Soebatsfontain	21	Hyposalic - Epileptic Regosol (Eutric)	Epileptic Regosol (Hyposalic, Eutric)
182	22 Soebatsfontain	25	Chromic - Leptic Cambisol (Dystric)	Leptic Cambisol (Dystric, Chromic)
212	22 Soebatsfontain	39	Eutric - Hyperskeletic Leptosol	Hyperskeletic Leptosol (Eutric)
205	22 Soebatsfontain	41	Lithic Leptosol	Lithic Leptosol
204	22 Soebatsfontain	51	Chromic - Epileptic Cambisol (Eutric)	Epileptic Cambisol (Eutric, Chromic)
210	22 Soebatsfontain	55	Arenic - Endopetric Durisol (Chromic Dystric)	Endopetric Durisol (Arenic, Chromic)
211	22 Soebatsfontain	58	Arenic - Endopetric Durisol (Chromic)	Endopetric Durisol (Arenic, Chromic)
199	22 Soebatsfontain	61	Hypocalcic - Epipetric Durisol (Chromic)	Hypocalcic Epipetric Durisol (Chromic)
198	22 Soebatsfontain	62	Eutric - Lithic Leptosol	Lithic Leptosol (Eutric)
200	22 Soebatsfontain	70	Rhodic - Endoleptic Cambisol (Eutric)	Endoleptic Cambisol (Eutric, Rhodic)
192	22 Soebatsfontain	74	Arenic - Epileptic Regosol (Hypereutric)	Epileptic Regosol (Hypereutric, Arenic)
193	22 Soebatsfontain	75	Lithic Leptosol	Lithic Leptosol
201	22 Soebatsfontain	80	Chromic - Epipetric Durisol	Duric Hypersalic Solonchak (Siltic)
191	22 Soebatsfontain	84	Chromic - Epileptic Cambisol (Eutric)	Epileptic Cambisol (Eutric, Chromic)
194	22 Soebatsfontain	86	Chromic - Epipetric Durisol	Epipetric Durisol (Chromic)
189	22 Soebatsfontain	92	Chromic - Epileptic Cambisol (Eutric)	Epileptic Cambisol (Eutric, Chromic)
190	22 Soebatsfontain	94	Dystric Leptosol	Haplic Leptosol (Dystric)
186	22 Soebatsfontain	97	Hypocalcic - Endopetric Durisol (Chromic)	Hypocalcic Duric Hypersalic Solonchak
185	22 Soebatsfontain	98	Chromic - Epileptic Cambisol (Dystric)	Epileptic Cambisol (Dystric, Chromic)
184	22 Soebatsfontain	99	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
531	22 Soebatsfontain	t1	Chromic - Epipetric Durisol	Duric Hypercalcic Solonchak
532	22 Soebatsfontain	t2	Aridic - Epipetric Durisol	Epipetric Durisol (Aridic)
533	22 Soebatsfontain	t3	Duric - Gypsic Solonchak (Hypersalic)	Duric Gypsic Hypersalic Solonchak
534	22 Soebatsfontain	t4	Aridic - Endopetric Durisol (Hypocalcic)	Hypocalcic Duric Hypersalic Solonchak (Aridic)
535	22 Soebatsfontain	t5	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
536	22 Soebatsfontain		Hypersalic - Duric Solonchak (Ochric)	Duric Hypersalic Solonchak (Siltic)
1173	24 Paulshoek	01	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1171	24 Paulshoek	03	Dystric Leptosol	Haplic Leptosol (Dystric)
1170	24 Paulshoek	04	Dystric Leptosol	Haplic Leptosol (Dystric)
1174	24 Paulshoek	10	Eutric Leptosol	Leptosol (Eutric)
1172	24 Paulshoek	12	Hypereutric - Lithic Leptosol	Lithic Leptosol (Hypereutric)
1168	24 Paulshoek	23	Hypereutric - Lithic Leptosol	Lithic Leptosol (Hypereutric)
1169	24 Paulshoek	24	Hypereutric Arenosol	Haplic Arenosol (Hypereutric)
1181	24 Paulshoek	27	Endoskeletic - Arenic Regosol (Eutric)	Haplic Regosol (Eutric, Endoskeletic, Arenic)
1182	24 Paulshoek	28	Eutric - Lithic Leptosol	Lithic Leptosol (Eutric)
1176	24 Paulshoek	30	Hypereutric - Lithic Leptosol	Lithic Leptosol (Hypereutric)
1180	24 Paulshoek	37	Dystric Leptosol	Haplic Leptosol (Dystric)
1175	24 Paulshoek	40	Haplic Solonchak	Haplic Solonchak
1183	24 Paulshoek	44	Episkeletic - Endoleptic Regosol (Dystric)	Endoleptic Regosol (Dystric, Episkeletic)
1184	24 Paulshoek	54	Eutric Leptosol	Haplic Leptosol (Eutric)
1186	24 Paulshoek	61	Chromic - Endoleptic Cambisol (Eutric)	Endoleptic Cambisol (Eutric, Chromic)
1177	24 Paulshoek	62	Arenic - Salic Fluvisol	Hypersalic Solonchak (Arenic)
1185	24 Paulshoek	65	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1178	24 Paulshoek	73	Calcaric - Lithic Leptosol (Hypereutric)	Lithic Leptosol (Calcaric, Hypereutric)
1165	24 Paulshoek	80	Hypereutric Fluvisol	Haplic Solonchak
1166	24 Paulshoek	81	Hypereutric Leptosol	Leptosol (Hypereutric)
1179	24 Paulshoek	83	Chromic - Endoleptic Cambisol (Hypereutric)	Endoleptic Cambisol (Hypereutric, Chromic)
1187	24 Paulshoek	87	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1164	24 Paulshoek	91	Hypereutric Fluvisol	Haplic Fluvisol (Hypereutric)
1189	24 Paulshoek	94	Eutric - Lithic Leptosol	Lithic Leptosol (Eutric)
1188	24 Paulshoek	96	Episkeletic - Epileptic Cambisol (Chromic Eutric)	Epileptic Cambisol (Eutric, Episkeletic, Chromic)

Appendix I List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
1155	25 Remhoogte	06	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1156	25 Remhoogte	07	Eutric - Lithic Leptosol	Lithic Leptosol (Dystric)
1151	25 Remhoogte	11	Eutric Leptosol	Haplic Leptosol (Eutric)
1167	25 Remhoogte	15	Hypereutric - Lithic Leptosol	Lithic Leptosol (Hypereutric)
1144	25 Remhoogte	22	Hypereutric - Arenic Fluvisol	Haplic Fluvisol (Hypereutric, Arenic)
1143	25 Remhoogte	23	Chromic?? - Calcaric Cambisol (Hypereutric)	Hypersalic Solonchak
1142	25 Remhoogte	24	Calcaric - Epileptic Cambisol (Episkeletic Chromic)	Epileptic Cambisol (Calcaric, Episkeletic, Chromic)
1152	25 Remhoogte	30	Eutric Leptosol	Haplic Leptosol (Eutric)
1141	25 Remhoogte	34	Dystric Leptosol	Haplic Leptosol (Dystric)
1150	25 Remhoogte	39	Eutric Leptosol	Haplic Leptosol (Eutric)
1153	25 Remhoogte	40	Humic - Lithic Leptosol (Dystric)	Lithic Leptosol (Humic, Dystric)
1154	25 Remhoogte	42	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1140	25 Remhoogte	45	Eutric Leptosol	Haplic Leptosol (Eutric)
1163	25 Remhoogte	46	Hypereutric Fluvisol	Haplic Fluvisol (Hypereutric)
1161	25 Remhoogte	64	Eutric Leptosol	Haplic Leptosol (Eutric)
1162	25 Remhoogte	65	Hypocalcic Calcisol	Calcic Solonchak
1158	25 Remhoogte	72	Dystric Leptosol	Haplic Leptosol (Dystric)
1159	25 Remhoogte	73	Hypereutric - Hyperskeletic Leptosol	Hyperskeletic Leptosol (Hypereutric)
1160	25 Remhoogte	74	Dystric Leptosol	Haplic Leptosol (Dystric)
1145	25 Remhoogte	78	Chromic?? - Epileptic Cambisol (Eutric)	Epileptic Cambisol (Eutric, Clayic, Chromic)
1157	25 Remhoogte	83	Eutric Leptosol	Haplic Leptosol (Eutric)
1149	25 Remhoogte	87	Eutric Leptosol	Haplic Leptosol (Eutric)
1146	25 Remhoogte	88	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1148	25 Remhoogte	96	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1147	25 Remhoogte	98	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
1190	25 Remhoogte	T1	Eutric Arenosol	Haplic Arenosol (Eutric)
1191	25 Remhoogte	T2	Calcaric - Arenic Regosol	Haplic Regosol (Calcaric, Arenic)
1192	25 Remhoogte	T3	Calcaric - Endoleptic Regosol	Endoleptic Regosol (Calcaric)
1193	25 Remhoogte	T4	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
231	26 Goedehoop	03	Skeletic - Epileptic Cambisol (Chromic Dystric)	Epileptic Cambisol (Dystric, Skeletic, Episiltic, Endoclayic)
278	26 Goedehoop	06	Chromic - Skeletic Cambisol (Hypereutric)	Haplic Cambisol (Hypereutric, Skeletic, Siltic, Chromic)
237	26 Goedehoop	07	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
236	26 Goedehoop	08	Chromic - Skeletic Cambisol (Hypereutric)	Haplic Cambisol (Hypereutric, Skeletic, Siltic, Chromic)
232	26 Goedehoop	12	Rhodic - Skeletic Cambisol (Dystric)	Haplic Cambisol (Dystric, Skeletic, Episiltic, Endoclayic)
230	26 Goedehoop	13	Dystric Leptosol	Hypersalic Solonchak (Siltic)
277	26 Goedehoop	17	Chromic - Skeletic Cambisol (Hypereutric)	Haplic Cambisol (Hypereutric, Skeletic, Siltic, Chromic)
233	26 Goedehoop	20	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic)
234	26 Goedehoop	25	Eutric Leptosol	Haplic Leptosol (Eutric)
249	26 Goedehoop	30	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
229	26 Goedehoop	33	Skeletic - Epileptic Cambisol (Chromic)	Epileptic Cambisol (Skeletic, Siltic, Chromic)
276	26 Goedehoop	37	Chromic - Skeletic Cambisol (Hypereutric)	Haplic Cambisol (Hypereutric, Skeletic, Chromic)
238	26 Goedehoop	38	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
235	26 Goedehoop	45	Eutric Leptosol	Haplic Leptosol (Eutric)
248	26 Goedehoop	50	Dystric Leptosol	Haplic Leptosol (Dystric)
247	26 Goedehoop	61	Hypersalic - Yermic Solonchak (Chloridic Eutric)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
239	26 Goedehoop	68	Hypereutric Fluvisol	Haplic Fluvisol (Hypereutric, Episiltic)
240	26 Goedehoop	69	Hypereutric - Skeletic Cambisol	Haplic Cambisol (Hypereutric, Skeletic, Siltic)
243	26 Goedehoop	74	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
242	26 Goedehoop	75	Hypereutric Fluvisol	Haplic Fluvisol (Hypereutric, Siltic)
241	26 Goedehoop	76	Hypereutric Fluvisol	Haplic Fluvisol (Hypereutric)
246	26 Goedehoop	80	Skeletic - Epileptic Cambisol (Chromic Hypereutric)	Epileptic Cambisol (Hypereutric, Skeletic, Siltic, Chromic)
245	26 Goedehoop	83	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
244	26 Goedehoop	94	Hypereutric Fluvisol	Haplic Fluvisol (Hypereutric, Episiltic)
275	26 Goedehoop	98	Dystric Leptosol	Haplic Leptosol (Dystric)
274	27 Luiperskop	00	Skeletic - Epileptic Cambisol (Eutric)	Epileptic Cambisol (Eutric, Skeletic)
273	27 Luiperskop	03	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
272	27 Luiperskop	16	Eutric - Lithic Leptosol	Lithic Leptosol (Eutric)
250	27 Luiperskop	28	Hypereutric Leptosol	Haplic Leptosol (Hypereutric, Siltic)
255	27 Luiperskop	35	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
253	27 Luiperskop	38	Dystric Leptosol	Haplic Leptosol (Dystric)
251	27 Luiperskop	39	Skeletic - Epileptic Cambisol (Chromic Hypereutric)	Epileptic Cambisol (Hypereutric, Skeletic, Siltic, Chromic)
257	27 Luiperskop	47	Dystric Leptosol	Haplic Leptosol (Dystric)
252	27 Luiperskop	48	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic)
254	27 Luiperskop	49	Skeletic - Epileptic Cambisol (Chromic Hypereutric)	Hypersalic Solonchak (Siltic)
256	27 Luiperskop	57	Hypereutric Leptosol	Haplic Leptosol (Hypereutric)
270	27 Luiperskop	60	Skeletic - Endoleptic Cambisol (Chromic Hypereutric)	Haplic Solonchak
267	27 Luiperskop	63	Dystric Leptosol	Haplic Solonchak (Siltic)
258	27 Luiperskop	68	Hypereutric - Skeletic Cambisol	Haplic Cambisol (Hypereutric, Skeletic)
271	27 Luiperskop	71	Dystric - Lithic Leptosol	Lithic Leptosol (Dystric)
266	27 Luiperskop	73	Eutric Leptosol	Haplic Leptosol (Eutric)
265	27 Luiperskop	74	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
261	27 Luiperskop	78	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic)
259	27 Luiperskop	79	Hypereutric Leptosol	HaplicLeptosol (Hypereutric)
269	27 Luiperskop	80	Chromic - Skeletic Cambisol (Eutric)	Haplic Cambisol (Eutric, Skeletic, Chromic)
268	27 Luiperskop	81	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic)
264	27 Luiperskop	84	Hypersalic - Yermic Solonchak (Chloridic)	Hypersalic Solonchak (Chloridic, Yermic, Siltic)
263	27 Luiperskop	94	Dystric Leptosol	HaplicLeptosol (Dystric)

Appendix I List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
262	27 Luiperskop	96	Hypereutric - Skeletic Cambisol	Haplic Cambisol (Hypereutric, Skeletic)
260	27 Luiperskop	99	Hypereutric - Skeletic Cambisol	HaplicCambisol (Hypereutric, Skeletic)
959	32 Elandsberg	09	Eutric - Stagnic Regosol	Stagnic Regosol (Eutric, Clayic)
958	32 Elandsberg	16	Episkeletic - Stagnic Regosol (Eutric)	Stagnic Regosol (Eutric, Episkeletic, Clayic)
965	32 Elandsberg	20	Episkeletic - Stagnic Regosol (Dystric)	Stagnic Regosol (Dystric, Episkeletic, EndoSiltic)
966	32 Elandsberg	23	Eutric - Stagnic Regosol	Stagnic Regosol (Eutric, Clayic)
960	32 Elandsberg	29	Episkeletic - Arenic Regosol (Eutric)	Haplic Regosol (Eutric, Episkeletic, Arenic)
979	32 Elandsberg	36	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
961	32 Elandsberg	39	Episkeletic - Arenic Regosol (Dystric)	Haplic Regosol (Dystric, Episkeletic, Arenic)
967	32 Elandsberg	40	Episkeletic - Stagnic Regosol (Eutric)	Stagnic Regosol (Eutric, Endoclayic)
978	32 Elandsberg	46	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
963	32 Elandsberg	48	Episkeletic - Arenic Regosol (Dystric)	Haplic Regosol (Dystric, Episkeletic, Arenic)
962	32 Elandsberg	49	Episkeletic - Arenic Regosol (Dystric)	Haplic Regosol (Dystric, Episkeletic, Arenic)
964	32 Elandsberg	57	Dystric - Episkeletic Regosol	Regosol (Dystric, Episkeletic)
977	32 Elandsberg	59	Episkeletic - Arenic Regosol (Dystric)	Haplic Regosol (Dystric, Episkeletic, Arenic)
968	32 Elandsberg	60	Episkeletic - Stagnic Regosol (Eutric)	Stagnic Regosol (Eutric, Clayic)
969	32 Elandsberg	62	Eutric - Stagnic Regosol	Stagnic Regosol (Eutric)
980	32 Elandsberg	68	Episkeletic - Arenic Regosol (Dystric)	Haplic Regosol (Dystric, Episkeletic, Arenic)
981	32 Elandsberg	70	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
973	32 Elandsberg	73	Episkeletic - Arenic Regosol (Dystric)	Haplic Regosol (Dystric, Episkeletic, Arenic)
974	32 Elandsberg	74	Dystric - Stagnic Regosol	Stagnic Regosol (Dystric, Clayic)
970	32 Elandsberg	84	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
982	32 Elandsberg	90	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
972	32 Elandsberg	92	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
971	32 Elandsberg	94	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
976	32 Elandsberg	97	Episkeletic - Stagnic Regosol (Dystric)	Stagnic Regosol (Dystric, Siltic)
975	32 Elandsberg	99	Dystric - Arenic Regosol	Haplic Regosol (Dystric, Arenic)
1216	33 Cape Peninsula	02	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1215	33 Cape Peninsula	03	Haplic Podzol	Haplic Podzol
1214	33 Cape Peninsula	05	Endoskeletic Podzol	Haplic Podzol (Endoskeletic)
1217	33 Cape Peninsula	11	Dystric - Humic Leptosol	Haplic Leptosol (Humic, Dystric, Greyic)
1213	33 Cape Peninsula	15	Endoskeletic - Gleyic Podzol	Gleyic Podzol (Endoskeletic)
1218	33 Cape Peninsula	20	Dystric - Humic Leptosol	Haplic Leptosol (Humic, Dystric, Greyic)
1201	33 Cape Peninsula	29	Gleyic Podzol	Gleyic Podzol
1202	33 Cape Peninsula	37	Endoskeletic - Gleyic Podzol	Gleyic Podzol (Endoskeletic)
1212	33 Cape Peninsula	41	Dystric - Humic Leptosol	Haplic Leptosol (Humic, Dystric, Greyic)
1203	33 Cape Peninsula	47	Endoskeletic Podzol	Haplic Podzol (Endoskeletic)
1211	33 Cape Peninsula	51	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1207	33 Cape Peninsula	54	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1206	33 Cape Peninsula	55	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1204	33 Cape Peninsula	57	Hyperdystric - Humic Leptosol	Haplic Leptosol (Humic, Hyperdystric, Greyic)
1200	33 Cape Peninsula	59	Endoskeletic - Gleyic Podzol	Gleyic Podzol (Endoskeletic)
1194	33 Cape Peninsula	60	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1208	33 Cape Peninsula	63	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1205	33 Cape Peninsula	67	Gleyic Podzol	Gleyic Podzol
1210	33 Cape Peninsula	70	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1209	33 Cape Peninsula	73	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1196	33 Cape Peninsula	86	Episkeletic - Gleyic Podzol	Gleyic Podzol (Episkeletic)
1198	33 Cape Peninsula	87	Endoskeletic - Gleyic Podzol	Gleyic Podzol (Endoskeletic)
1195	33 Cape Peninsula	91	Episkeletic Podzol	Haplic Podzol (Episkeletic)
1197	33 Cape Peninsula	96	Gleyic Podzol	Gleyic Podzol
1199	33 Cape Peninsula	99	Gleyic Podzol	Gleyic Podzol
1258	39 Nareis	02	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1257	39 Nareis	03	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1246	39 Nareis	08	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1255	39 Nareis	10	Hyperskeletic - Paralithic Leptosol	Hyperskeletic Paralithic Leptosol
1256	39 Nareis	13	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1260	39 Nareis	21	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1245	39 Nareis	26	Cutanic Luvisol	Cutanic Luvisol
1247	39 Nareis	29	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1262	39 Nareis	30	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1261	39 Nareis	32	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1248	39 Nareis	38	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1267	39 Nareis	43	Hypercalcic - Epipetric Calcisol	Hypercalcic Epipetric Calcisol
1244	39 Nareis	46	Cutanic Luvisol	Cutanic Luvisol
1249	39 Nareis	47	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1268	39 Nareis	52	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1250	39 Nareis	55	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1266	39 Nareis	63	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1269	39 Nareis	70	Cutanic Luvisol	Cutanic Luvisol
1251	39 Nareis	76	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1264	39 Nareis	81	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1263	39 Nareis	82	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1252	39 Nareis	88	Calcaric - Endoleptic Regosol	Endoleptic Regosol (Calcaric)
1265	39 Nareis	91	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1254	39 Nareis	93	Cutanic Luvisol	Cutanic Luvisol

Appendix I

List of soil units

No.	Observatory	ha	Soil unit (WRB 1998)	Soil unit (WRB 2006)
1253	39 Nareis	95	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1243	40 Duruchaus	02	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1235	40 Duruchaus	06	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1242	40 Duruchaus	11	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1234	40 Duruchaus	17	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1241	40 Duruchaus	21	Hypocalcic - Endoleptic Calcisol	Endoleptic Hypocalcic Calcisol
1240	40 Duruchaus	22	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1239	40 Duruchaus	23	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1237	40 Duruchaus	24	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1236	40 Duruchaus	25	Hypercalcic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol
1233	40 Duruchaus	28	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1238	40 Duruchaus	33	Hypocalcic - Endoleptic Calcisol	Endoleptic Hypocalcic Calcisol
1230	40 Duruchaus	37	Hyperskeletic - Paralithic Leptosol	Hyperskeletic Paralithic Leptosol
1231	40 Duruchaus	45	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1232	40 Duruchaus	46	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1229	40 Duruchaus	49	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1219	40 Duruchaus	51	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1226	40 Duruchaus	63	Hypocalcic Calcisol	Hypercalcic Calcisol
1227	40 Duruchaus	67	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1228	40 Duruchaus	69	Episkeletic - Epileptic Calcisol (Hypercalcic)	Epileptic Hypercalcic Calcisol (Episkeletic)
1225	40 Duruchaus	74	Hyperskeletic - Paralithic Leptosol	Hyperskeletic Paralithic Leptosol
1222	40 Duruchaus	82	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1220	40 Duruchaus	90	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
1221	40 Duruchaus	91	Hypercalcic - Endopetric Calcisol	Hypercalcic Endopetric Calcisol
1223	40 Duruchaus	95	Episkeletic - Endoleptic Calcisol	Endoleptic Calcisol (Episkeletic)
1224	40 Duruchaus	96	Episkeletic - Epipetric Calcisol (Hypercalcic)	Hypercalcic Epipetric Calcisol (Episkeletic)
t = additional transect profile				
ha = no. of hectare plot of the observatory				

Appendix II Abbreviation sheet for data files

1. profile data

Fieldname	Content	unit
Number	profile number (linkage with horizon data)	
Date	date of sampling	
Observatory	observatory (e.g. 04 Toggekry 250)	
Habitat_No	habitat number of the plot	
Rank_Div	adjusted ranking number of the plot in the observatory	
Ranking	ranking number of the plot in the observatory	
Hectare ID	plot number in the observatory	
Lat	latitude in dec-degree	
Long	longitude in dec-degree	
Stone_coverage_t	total coverage of stone pavement(>2mm)	%
Stone_coverage < 2	stones < 2 cm	%
Stone_coverage 2-6	stones 2 – 6 cm	%
Stone_coverage 6-20	stones 6 – 20 cm	%
Stone_coverage 20-60	stones 20 – 60 cm	%
Stone_coverage >60	stones > 60 cm	%
depth of survey	total depth of the profile / borehole	m
crust	depth of limitation by crusts	m
bedrock	depth of limitation by bedrock	m

Appendix II Abbreviation sheet for data files

2. horizon data

Fieldname	Content	unit
Number	profile number	
Lab_number	internal sample number	
horizon number	number of horizon	
UB	upper border of horizon	m
LB	lower border of horizon	m
MUNS_TR	colour Munsell dry	
MUNS_FE	colour Munsell wet	
texture field	texture class (KA4) by finger test	
clay*	derived by texture class (KA4)	
silt*	derived by texture class (KA4)	
sand*	derived by texture class (KA4)	
Coarse fragments (field)	Content of fragments > 2 mm	Vol. %
Clay	clay (< 2 µm)	%
fine silt	fine silt (2 - 6.3 µm)	%
medium silt	medium silt (6.3 - 20 µm)	%
coarse silt	coarse silt (20 - 63 µm)	%
total silt*	total silt (2 - 63 µm)	%
fine sand	fine sand (63 - 200 µm)	%
medium sand	middle sand (200 - 630 µm)	%
coarse sand	coarse sand (630 - 2000 µm)	%
total sand*	total sand (63 - 2000 µm)	%
texture lab	texture class (KA4) by analysis	
sandtexture	sandcombination	
BD	bulk density	g $cm^{3\ -1}$
PH_H_2O	pH value in water extract(1:2.5)	pH
PH_CaCl_2	pH value in $CaCl_2$ extract(1:2.5)	pH
$EC_{2.5}$	el. conduct. in water extract (1:2.5)	µS cm^{-1}
EC_5	el. conduct. in water extract (1:5)	µS cm^{-1}
C_T	total carbon	%
C_A	inorganic carbon	%
C_O*	organic carbon	%
CN_ratio*	organic C/N ratio	
N_T	total nitrogen	%
S_T	total S	g kg^{-1}
SI_T	total Si	%
AL_T	total Al	%
NA_T	total Na	g kg^{-1}
K_T	total K	g kg^{-1}
CA_T	total Ca	g kg^{-1}
MG_T	total Mg	g kg^{-1}
P_T	total P	g kg^{-1}
TI_T	total Ti	g kg^{-1}
FE_T	total Fe	g kg^{-1}
MN_T	total Mn	g kg^{-1}

Appendix II Abbreviation sheet for data files

2. horizon data (continued)

Fieldname	Content	unit
CR_T	total Cr	mg kg^{-1}
CU_T	total Cu	mg kg^{-1}
NI_T	total Ni	mg kg^{-1}
ZN_T	total Zn	mg kg^{-1}
PB_T	total Pb	mg kg^{-1}
BA_T	total Ba	mg kg^{-1}
SR_T	total Sr	mg kg^{-1}
ZR_T	total Zr	mg kg^{-1}
CL_GBL	chloride in water extract (1:1)	mg l^{-1}
FL_GBL	fluoride in water extract (1:1)	mg l^{-1}
BR_GBL	bromide in water extract (1:1)	mg l^{-1}
NO3_GBL	nitrate in water extract (1:1)	mg l^{-1}
NO2_GBL	nitrite in water extract (1:1)	mg l^{-1}
SO4_GBL	sulfate in water extract (1:1)	mg l^{-1}
HCO3_GBL	carbonate in water extract (1:1)	mg l^{-1}
CA_GBL	Ca in water extract (1:1)	mg l^{-1}
MG_GBL	Mg in water extract (1:1)	mg l^{-1}
K_GBL	K in water extract (1:1)	mg l^{-1}
NA_GBL	Na in water extract (1:1)	mg l^{-1}
CEC_E	effective cation exchange capacity	$mmol_c$ kg^{-1}
K_A	exchangeable K	$mmol_c$ kg^{-1}
NA_A	exchangeable Na	$mmol_c$ kg^{-1}
MG_A	exchangeable Mg	$mmol_c$ kg^{-1}
CA_A_M	exchangeable Ca (measured)	$mmol_c$ kg^{-1}
CA_A_K	exchangeable Ca (corrected)	$mmol_c$ kg^{-1}
H_A	exchangeable H	$mmol_c$ kg^{-1}
AL_A	exchangeable Al	$mmol_c$ kg^{-1}
K_AC	K in NH_4-acetate extract	$mmol_c$ kg^{-1}
NA_AC	Na in NH_4-acetate extract	$mmol_c$ kg^{-1}
MG_AC	Mg in NH4-acetate extract	$mmol_c$ kg^{-1}
CA_AC	Ca in NH4-acetate extract	$mmol_c$ kg^{-1}
FE_O	oxalate soluble Fe	g kg^{-1}
FE_D	dithionite soluble Fe	g kg^{-1}
MN_D	dithionite soluble Mn	g kg^{-1}

* calculated
KA4 = AK Boden 1994
[-1] indicates 'not analysed'
[-9] indicates 'below detection limit'

Appendix III & IV → CD-Rom

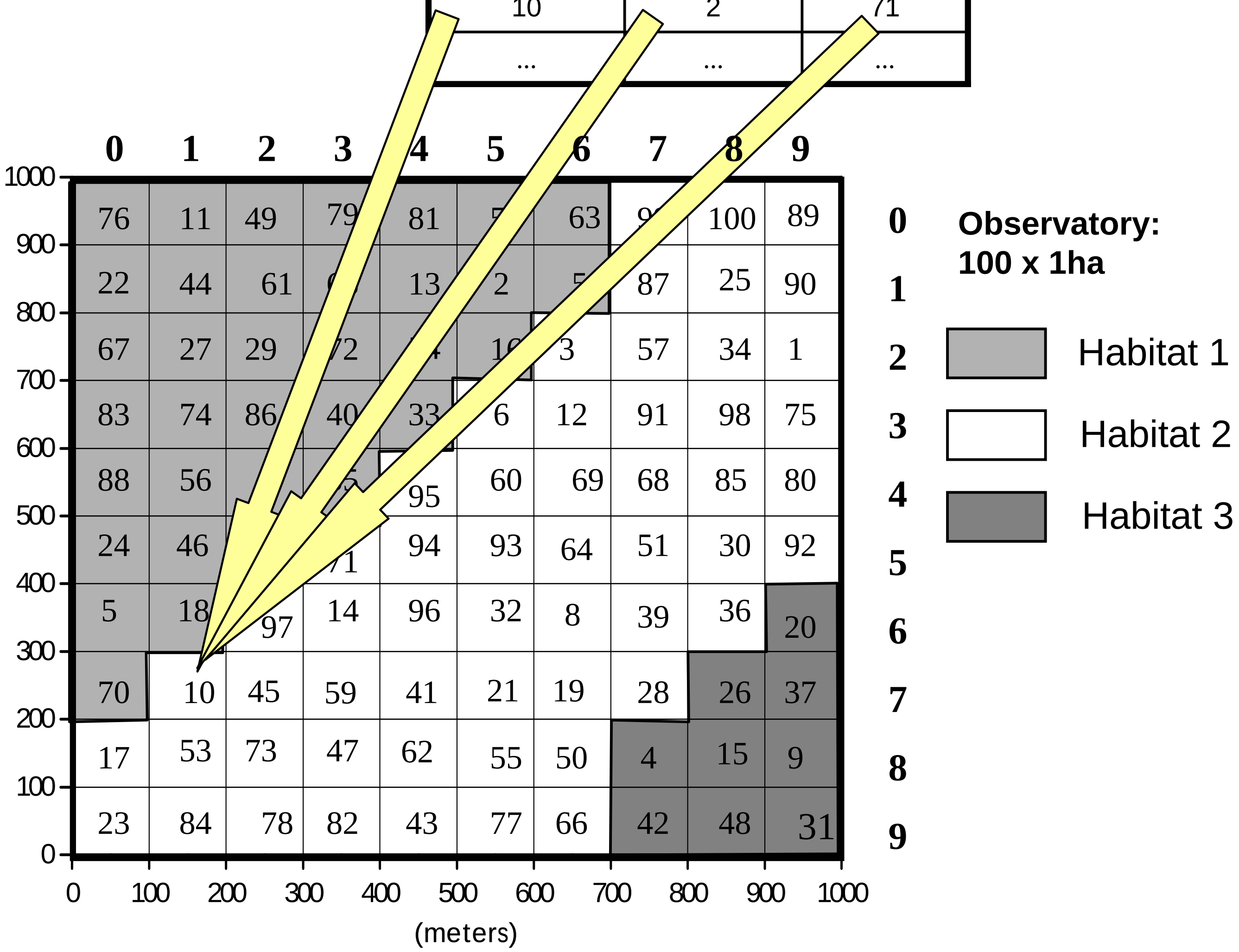
Appendix V

<u>Illustration of the applied method for the systematic, stratified, random selection with priorisation (ranking procedure)</u>

The hypothetical example shows an observatory with three different habitats.

Result of the calculation procedure showing ranking number, habitat type, and position within the observatory (right chart, below observatory scheme with habitats and ranking numbers)

Ranking	Habitat	Coor-dinates
1	2	29
2	1	15
3	2	26
4	3	87
5	1	60
6	2	53
7	1	24
8	2	66
9	3	89
10	2	71
...	...	...



Appendix V

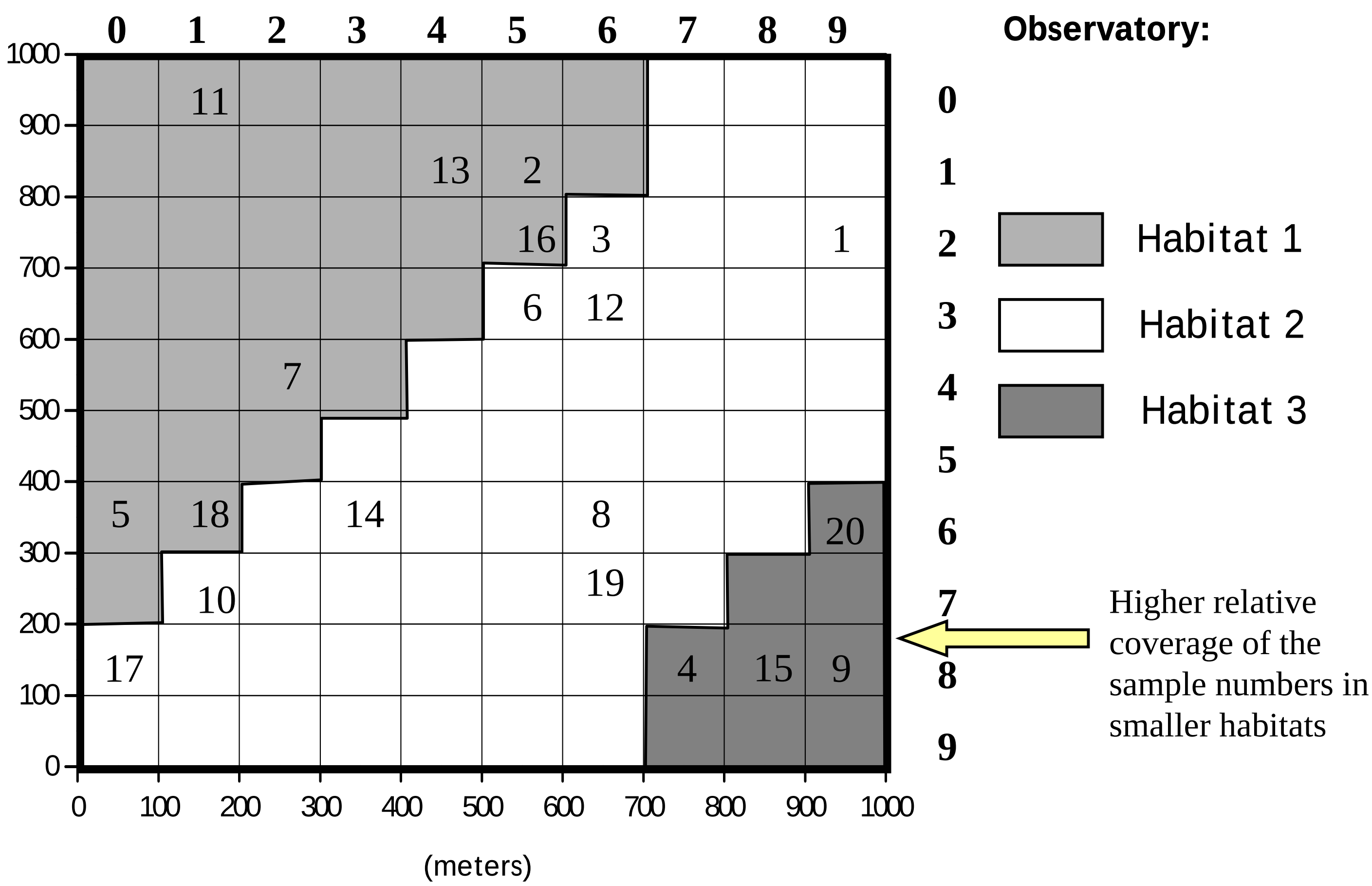
<u>Illustration of the applied method for the systematic, stratified, random selection with priorisation (ranking procedure)</u>

The hypothetical example shows an observatory with three different habitats.

Number of samples per habitat for different survey intensities

Habitat	Number of samples (n)		
	n = 50	n = 20	n =10
1 = 35 ha	18	7	3
2 = 56 ha	23	9	5
3 = 9 ha	9	4	2

Distribution of sample sites with total samples n = 20



Appendix VI

Access scheme to soil info via www.biota-africa.org

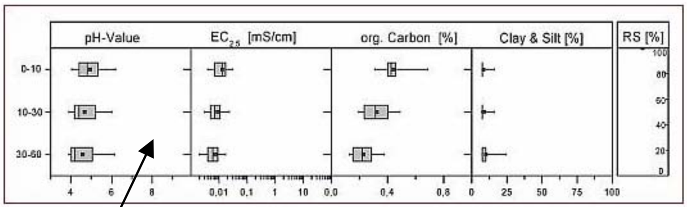
No.	Observatory	ha	Soil unit (WRB 1998)
116	02 Mutompo	04	Dystric - Ferralic Arenosol
113	02 Mutompo	06	Dystric - Ferralic Arenosol
115	02 Mutompo	14	Dystric - Ferralic Arenosol
114	02 Mutompo	15	Dystric - Ferralic Arenosol

1. Identification of selected profile by appendix I (via ha.-no.)

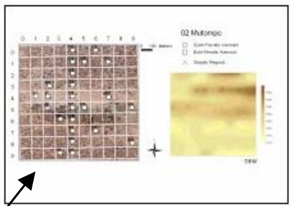
2. Online access to selected observatory via www.biota-africa.org

3. Selection of i) overwiev graph, ii) soil map, or single profile via highlighted ha-plots

4. Single profile information with i) profile photo, ii) site photo, and iii) profile graph of selected properties



Box-Whisker-overview of selected soil properties in three depths (cm) on the observatory (RS = rooting space / m³)



Map with location of soil units on the observatory

plot	Habitat	Rank
Photograph available		
Soil data available		
00	1	49
01	1	78
02	1	92
03	1	30
04	1	79
05	1	59
06	1	1
07	1	84
08	1	71
09	1	62
10	1	99
11	1	39
12	1	82
13	1	72
14	1	32
15	1	5

Ranking of the 1ha-plots

	0	1	2	3	4	5	6	7	8	9
0	49	78	92	30	79	[illegible]	1	84	71	62
1	99	39	82	72	32	5	[illegible]	6	83	53
2	64	47	21	67	12	66	81	97	100	94
3	85	73	11	89	90	80	43	[illegible]	57	75
4	17	7	44	56	9	29	61	13	34	48
5	63	50	4	20	25	10	58	54	28	8
6	37	27	31	14	19	35	41	46	38	18
7	60	98	16	33	76	52	3	23	40	65
8	96	36	77	26	88	68	93	42	74	15
9	70	69	87	2	24	91	51	[illegible]	45	95

Habitat types of the 1ha-plots

	0	1	2	3	4	5	6	7	8	9
0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	3	3	2	2	2	2	2	2	2	2
5	4	4	4	4	4	4	4	4	5	5
6	3	3	4	4	2	4	4	4	5	5
7	1	1	1	1	1	2	2	2	2	2
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1

Overview graph for the observatory

Soil map of the observatory

Observatory scheme with ranking numbers

Observatory scheme with habitat numbers

Profile photo

Site photo

Profile graph

Profil photograph P113

Left : P113S - BIOTA_380_P113s(1517)
Right: P113 - BIOTA_379_P113(1515) (dry)

Soil properties graph of P113

Show legend