The Scale-Dependent Variability of Topsoil Properties Reflecting Ecosystem Patchiness in Drylands of Southern Africa

Dissertation

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In memoriam to Hendrik P. Prinsloo, my friend and fellow student during my semester abroad in Stellenbosch, with whom I dug my first South African soils.

The memory of your enthusiasm for soils and your affection for your country and its people made me smile during the tough times of this thesis.

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Abbreviations and Acronyms

Al_t	total aluminium
Anions_{we}	waterextractable anions
Ba_t	total barium
BIOTA	Biodiversity Monitoring Transect Analysis in Africa
Br_{we}	waterextractable bromium
BSC	biological soil crust
C_{inorg}	inorganic carbon
C_{mic}	microbial biomass
C_{org}	organic carbon
Ca_t	total calcium
Ca_{we}	waterextractable calcium
$\mathrm{Cations}_{we}$	waterextractable cations
cfS	coarse fine sand
Cl_{we}	waterextractable chlorine
Cr_t	total chromium
cS	coarse sand
cSi	coarse silt
Cu_t	total copper
DEM	digital elevation model
$\mathrm{EC}_{2.5}$	electrical conductivity in 1:2.5 solution
EC_5	electrical conductivity in 1:5 solution
F_{we}	waterextractable fluorine
Fe_t	total iron
Fe_{we}	waterextractable iron
ffS	finest fine sand
fS	fine sand
fSi	fine silt
GWC	gravimetric water content
HCO_{3we}	waterextractable bicarbonate
IR	single ring infiltration rate
K_t	total potassium
K_{dl}	double lactate soluble potassium = plant available potassium
K_{we}	waterextractable potassium
MAP	mean annual precipitation
m asl	meters above sea level
Mg_t	total magnesium
Mg_{we}	waterextractable magnesium
Mn_t	total manganese
MSC	mineral soil crust
mS	medium sand
mSi	medium silt
N_t	total nitrogen

n.a.	not analysed
Na_t	total sodium
Na_{we}	waterextractable sodium
Ni_t	total nickel
NO_{2we}	waterextractable nitrite
NO_{3we}	waterextractable nitrate
Osm. Pot.	osmotic potential
P_t	total phosphorus
P_{dl}	double lactate soluble phoshorus = plant available phosphorus
PGM	phytogenic mounds
pH_{H2O}	pH measured in aqua demin
pH_{CaCl2}	pH measured in calcium chloride solution
Pb_t	total lead
S_t	total sulphur
SD	standard deviation
Si_t	total silicon
SO_{4we}	waterextractable sulfate
Sr_t	total strontium
SSU	small stock unit
Ti_t	total titanium
TRB	total reserve in bases [$cmol_c$ kg^{-1}]
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
WRB	World Reference Base for Soil Resources
Zn_t	total zinc
Zrt	total zirconium

1 Introduction

The conservation of our world's biodiversity is regarded as indispensable for the existence of mankind (UNEP, 1995).

Plant and animal species provide sources of food, fibre, medicine and fuel; the biological diversity of these species assures a great variety of ecological services such as the sustainment of fresh water, soil fertility and micro-climate, the mitigation of floods and droughts, the pollination of crops and the control of agricultural pests, to name but a few. It maintains the resilience of ecosystems to alterations in environmental conditions and to perturbations (Cardinale *et al.*, 2006; Moore, 2005; Tilman, 2000; Kunin & Lawton, 1996) and as a result affects the sustainability of a region's economical development. Especially the developing countries depend economically on agro-ecosystems, which reflects the fact that employment, output and export are directly linked to the ecological functioning of ecosystems (Perrings, 2006). Further, biodiversity bears in itself a potential for commercial use with regard to bioprospecting - the exploration and marketing of genetic and biochemical resources in plant or animal species for medicinal and biotechnological purposes, which is particularly a potential source of income for some less developed countries (Chapin III *et al.*, 2000; Wynberg, 2002). Apart from these economical considerations, biodiversity is worth protecting for ethical and aesthetical reasons alone, factors which in turn generate profitably in terms of eco-tourism.

Although they are of such vital importance for mankind, the diversity of species and species composition is endangered. According to a species-area relationship based estimation of Wilson (1992), 27,000 species become extinct annually, which corresponds approximately to one species per every twenty minutes. Saier (2006) states a rate of 8,000 species per year. However, the genetic resources of the species are irrecoverably lost and with it potential substances of pharmacological or technological interest. Main causes for the extinctions of species are transformations and destructions of habitats, mostly for food production, overexploitation of resources, introduction of neophytes and the resulting displacement of indigenous species and climate change (Myers, 2003; Gisladottir & Stocking, 2005; Delbaere, 2005; Perrings, 2000).

The global significance of biodiversity was recognised and the growing concern regarding its protection acknowledged in 1992 with Agenda 21 (UNCED, 1993). Since then, major research projects have been launched and strategies for the protection of species diversity developed. Hotspots of biodiversity were identified (Myers *et al.*, 2000) that are most threatened and in need of protection, since the percentage of endemic species is exceptionally high in these areas and also jeopardised by enhanced habitat loss and transformation. Amongst them are the Cape Region and the Succulent Karoo of South Africa.

Further ecosystems need to be conserved since they provide the means of existence for a large and rapidly growing proportion of the population in arid and semi-arid areas like in the African savannas (Scholes & Archer, 1997). The vast drylands are particularly vulnerable to overexploitation and climate change, and are threatened by the phenomenon of desertification (Akhtar-Schuster & Martius, 2003). Bush encroachment and erosion already led to a severe decline in the productivity of rangelands (de Klerk, 2004; Kempf, 1997); the occurrence of degradation patches indicates catastrophic shifts between ecosystem states (Rietkerk *et al.*, 2004). In numerical values, MacKinnon & MacKinnon (1986) stated a habitat loss of 46 % for Namibia alone; according to Wynberg (2002) in South Africa 26.5 % of the terrestrial landsurface has been transformed or heavily degraded. The need for a better understanding of processes and the relation of feedback-mechanisms on different scales as well as an interdisciplinary exchange and collaboration has been diagnosed by several authors (Rietkerk *et al.*, 2004; van de Koppel *et al.*, 2002; Wätzold *et al.*, 2006). Since biodiversity is highly related to geodiversity (Leser & Nagel, 2001), it was postulated that especially abiotic factors have to be included into these considerations.

Soil, as one major factor of terrestrial ecosystems, is to a great extent determined by geology, topography and climate and therefore reflects the combined effects of abiotic factors on biodiversity. The other way round, soil properties are directly affected by biotic factors as well as anthropogenic use. Impacts of landuse and climate change on ecosystem stability might therefore be predicted by investigations of mutual dependencies between pedo- and biodiversity, an approach recently taken by Petersen (2008). The understanding of the interactions on various spatial scales opens the door to the derivation of sustainable management practices under a variety of natural conditions. Especially investigations of soil patchiness on the small scale, for instance the role of soil crusts as a major factor affecting rainfall infiltration, might lead to a better understanding of erosion and other degradation processes (Mills & Fey, 2004b). Despite the relevance of soils within the biodiversity discussion, few research groups address this issue and diversity of soils and soil properties as well as their interactions with vegetation still have a low significance within ecology and biodiversity research (Ibáñez *et al.*, 2005).

The project Biodiversity Transect Monitoring Analysis in Southern Africa (BIOTA South), which is funded by the German Federal Ministry of Education and Research, addresses the above-mentioned issues (see www.biota-africa.org). Its first phase was launched in January 2000 as a contributing research project to the International Diversitas programme, the goals of the United Nations Convention on Biodiversity (UNCBD), the United Nations Convention to Combat Desertification (UNCCD) and the Johannesburg Plan of Action of the World Summit on Sustainable Development. The objectives of this project are the assessment, long-term monitoring and causal analysis of changes of biodiversity as driven by anthropogenic landuse or climate change as well as the identification of biotic and abiotic drivers and processes. Investigations are conducted on 35 standardised biodiversity observatories along a transect from the Cape to the northern border of Namibia, which covers different landuse types, rainfall intensities and regimes and important biomes. The design and investigation schemes of these observatories allow longterm monitoring on the one hand, and a maximum data comparability between various research disciplines. By interdisciplinary collaboration between natural scientists, economists and ethnologists, predictions can be derived, sustainable management guidelines and restoration measures developed and tools for decision making and action deduced. Further, capacity building is part of the objectives.

This work was conducted in Phase II of the BIOTA South project from 2003 - 2006. Embedded in the Subproject S02, "Edaphical diversity and biodiversity in mutual dependence", this work analyses the scale-dependent variability of topsoil properties reflecting ecosystem patchiness in two biomes of southern Africa; the southern Namibian Nama Karoo and the northwestern South African Namaqualand. The research task was approached by addressing the following key questions:

- Which small-scale patterns occur in soilphysical and soilchemical properties? How are they linked to larger scales?
- What are the drivers of patterns?
- Which processes lead to the development of soil patchiness?
- To which degree differs ecosystem patchiness in the studied biomes?
- What are the implications for landuse options, climate change and vulnerability?

2 Material and Methods

2.1 Study Areas and Integration in the BIOTA Research Concept

The investigations were conducted on three sites along the BIOTA Southern Africa transect (Fig. 2.1) and were part of an integrated research approach (www.biota-africa.org).

The BIOTA transect ranges basically in north-south direction from the Kavango in the Republic of Namibia to the Cape in the Republic of South Africa, covering a broad range of rainfall regimes as well as different geological and topographical units. In addition, it comprises two minor transects in east-west orientation from the coast to central parts of Namibia. Along those transects, 35 standardised long-term monitoring sites, so-called biodiversity observatories, were established, each 1 x 1 km in size, subdivided into a one hundred hectare plots. Most of the observatories have been established during Phase I of the BIOTA project (2000 - 2003); since then, researchers of various disciplines conducted their investigations, following standardised scales and methods, which led to a dense and interdisciplinary highly comparable data base which was available for this study. The examinations are supplemented by data from climate stations that had been established on 18 observatories.

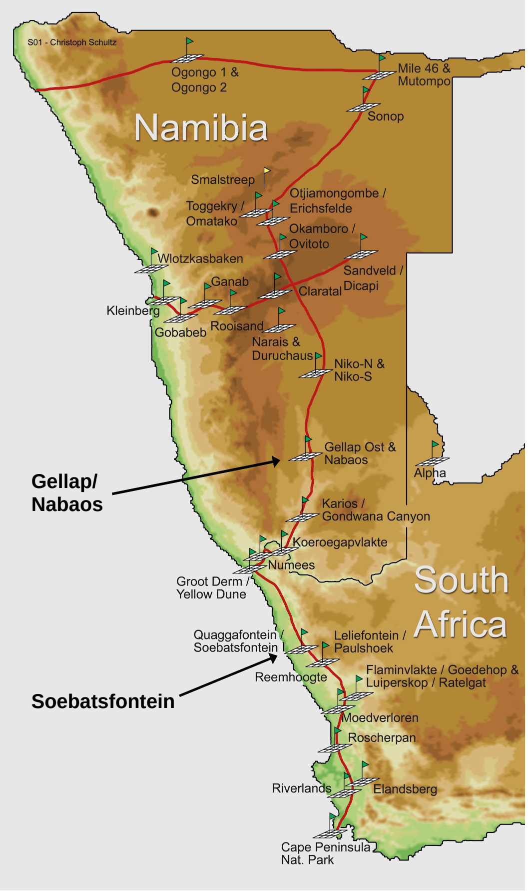

Fig. 2.1: BIOTA Southern Africa transect with observatory locations

For investigations of small scale variability of soil properties, three sites along the transect were selected that cover different parts of the rainfall regime and also address different key questions. Those are as follows:

Gellap Ost and Nabaos The observatories Gellap Ost and Nabaos are two adjacent twin observatories in the Nama Karoo of southern Namibia, approx. 30 km southeast of the city Keetmanshoop. The Nama Karoo is a term describing a dwarf shrub savanna highly adapted to aridity with low densities of grasses, dwarf shrubs and sporadic small trees. Annual rainfall is low; a mean of approx. 150 mm/a is spent as summer rainfall from February to April (BIOTA weather data: www.biota-africa.org). Parent material for the development of soils is clay shist and predominant texture is loamy sand. Soils have been classified as Cambisols, Regosols and Leptosols (Petersen, 2008).

While the Gellap Ost Observatory is part of a governmental research farm with low stocking densities, the Nabaos Observatory belongs to communal land of the Nama and is characterised by strong overgrazing due to rotational grazing (Kuiper, 2000; Akhtar-Schuster, 2002; Kuiper & Meadows, 2002). The impact of these different land-use systems on the rangelands is strikingly presented by a sharp contrast in vegetation cover and composition along the fenceline; while land on the Gellap side shows a high coverage with grasses, including the economically most valuable fodder plant *Stipagrostis uniplumis*, on the Nabaos commonage, perennial grasses cannot establish due to the heavy grazing pressure. The veld appears bare during dry season; only after rain events mass germination of annual species turns the rangeland green and provides biomass with high fodder quality (Wolkenhauer, 2003).

Soebatsfontein The Soebatsfontein Observatory is located in the Succulent Karoo of Namaqualand, approx. 30 km east of the atlantic coast line and 80 km south of the city Springbok. Despite very low annual rainfall of 130 mm, mostly spent during August and September, Namaqualand is characterised by and famous for its very diverse vegetation consisting to > 50% of succulent plants and geophytes (Desmet, 2007). 4,849 species have been described in this area 40% of which are endemic (Hilton-Taylor, 1996). Thus, Namaqualand has the status as a biodiversity hotspot and is regarded as a high priority region for conservation measurements (Myers *et al.*, 2000).

Soils are derived from granitic and gneissic parent materials and of sandy to loamy texture. The high spatial sequence of vegetation and soil patterns on the small scale is amongst other things related to the occurrence of "heuweltjies" (Afrikaans: "little hills"). The genesis of heuweltjies is not completely discovered yet (see Chapter 3.3.4), most authors regard them as fossil termite mounds that have been transformed by mammal activity and geochemical processes after climate change. However, soils at the margin of heuweltjies contain hard, biogene silicic crusts ("dorbank" or "hardpan") and calcareous crusts (calcretes) resulting in soil classification as Durisols and Calcisols. Additional soil types identified by Petersen (2008) are Cambisols, Arenosols and Leptosols. Further causes for the high pedo- and biodiversity are topographical variability (alternating flats and mountain slopes) as well as the influence of fogs because of the nearby ocean (Esler & Cowling, 1993).

The area is used for communal live stock grazing. Erosion rins and gullies and heuweltjies reduced in vegetation cover indicate a degradation of the veld and thus the endangerment of biodiversity and rangeland quality.

2.2 Field Methods

2.2.1 Field Campaigns

Field work was conducted from 2004 to 2006 in five field campaigns:

- 02/2004 - 03/2004. Six weeks field campaign in Namibia and South Africa. Selection of study sites, development of work concept.
- 08/2004 - 10/2004. Eight weeks field campaign in Namibia and South Afria, focus on Namaqualand
- 02/2005 - 04/2005. Ten weeks field campaign in Namibia and South Africa, focus on Nama Karoo
- 08/2005 - 09/2005. Six weeks field campaign in Namibia and South Africa, focus on central Namibian thornbush savanna
- 08/2006 - 09/2006. Six weeks field campaign in Namibia and South Africa. Finalisation of field work on all study sites

2.2.2 General Approach

The investigations are based on the assumption that landscapes can be described as nested units in four different scales as follows:

- D1: landscape; dimension approx. 1 to several km^2 (e.g. Succulent Karoo)
- D2: habitat = landscape subunit; 1000 m^2 to $<$ 1 km^2 (i.e. mountain top with outcrops, slope, flats)
- D3: mesostructures = habitat subunit; several m^2 to 1000 m^2 (i.e. heuweltjie centre, rivier (dry river bed), rock fringe below outcrops)
- D4: microstructures = mesostructure subunit; dm^2 to m^2 (i.e. open soil, soil with biological soil crusts (BSC), soils below shrub canopies)

The underlying working hypothesis presumes that parametric ratios between structures of the same D-unit are similar within different units of the superior hierarchical level. That means that soil areas covered by biological soil crusts (BSC) on the D3-unit "heuweltjie centre" show different physico-chemical properties to biocrusted soils in the D3-unit ”matrix” between the heuweltjies; comparing each of the two BSC-sites with adjacent open soil samples, however, will reveal that obtained differences will be of the same magnitude on the heuweltjie centre and the matrix-unit.

To test this hypothesis, sample collection was conducted according to the following procedure:

- Definition of the subunits on four scales for each observatory
- Selection of representative small scale study sites in the magnitude of approx. 10 x 10 to 50 x 50 m. These represent the most extensive D3-units
- Tachymetric survey of the sites (approx. 3000 coordinates on 10 x 10 m) including the survey of all D3 and D4-structures as well as the location of sampling and test-sites
- Mapping of perennial plants, erosion structures and soil crusts via attribute function of the tachymeter
- sampling (2.2.3)
- conduction of field tests (2.2.5, 2.2.6)
- laboratory analysis (2.3)

2.2.3 Basic Soil Data

The standard observation of soil types on an observatory scale along the transect has been investigated by Petersen (2008) since the beginning of BIOTA Phase I and was used as background data for basic assumptions concerning the concept of the fieldwork and the interpretation of the derived data sets. This standard procedure for the assessment of soil inventory on the observatories comprised the construction of soil pits 4 m south of the centre point of 20 to 25 hectare plots following a standardised ranking order. For the practical application of the ranking procedure, a computer programme was designed, which determined a priority listing of all 100 sites of an observatory following the input of the habitat unit of each hectare. The sampling procedure is a stratified sampling with random distribution within strata. In addition, the programme works with the D´Hondt highest number method. As the ranking order is based on the square root of the habitat size, the rarer habitat units on the square kilometre are uprated. In the same rank, on average 20 areas were botanically monitored, in order to obtain information on plant diversity and coverage within these plots.

The soil pits were photographed and the soil was described and sampled according to the BIOTA standard procedure as described in Petersen (2008). The samples were analysed in Germany with regard to a set of standard parameters (see Tab. 2.1).

Deep Profile Data In addition to the BIOTA soil assessment data, on every small scale study site one soil profile was dug, described and sampled to derive information on soil properties in depth. An overview of main soil properties and classification of reference profiles for most D3-units is provided in the Appendix (A.1 and B.1).

Topsoil Data Most data for the determination of small scale variability of soils and interaction with plants was derived from topsoil analysis according to another standardised procedure referred to as miniprofile sampling. Five miniprofiles were sampled on each D4 unit to assure statistical significance. Sampling was conducted in three layers, 0-1, 1-5 and 5-10 cm in depth to identify in-depth variations and pedodermis effects described by Mills (2003). In total, 861 soil samples were sampled.

2.2.4 Tachymetric Survey

For the survey of small scale topography, a tachymeter of the type Leica TCRP 1201 was used. A tachymeter is a kind of theodolite and capable of - as the greek word indicates - rapid measurements (Petrahn, 1996). The principle of this survey system is the simultaneous high precision measurement of angle by using a centralised dual axis compensator and the higly accurate determination of the distance with laser techniques. Since the tachymeter is motorised and equipped with an automatic target recognition system, a power search function and a remote control unit, it is possible to run the survey in one-"man" operation. For this purpose, a reflector, in this case a prism, is fixed to a bar with a defined length and an attached level. The operator places the reflector bar on the point to be measured, levels it and activates the measurement with the remote control. During the measurement process, a coaxial, invisible infrared laser beam is sent out from the device, reflected by the prism, captured by a sensitive photo receiver and then converted into an electrical signal (Leica, 2007b). After this signal was digitalised and recorded, the distance is determined by means of modern phase measurement techniques. Simultaneously, both, the horizontal and vertical angle are measured based on a coded glass circle and two CCD arrays that convert the codes into relative angle information. These informations are additionally corrected by the tilting-axis error that is determined beforehand and stored in the instrument, and the momentary component of the vertical-axis tilt, transverse to the line of sight (Bayoud, 2007).

Within 1 - 2 seconds, depending on the setting, the measurement is completed, as indicated by an audible signal. Moreover, it is possible to provide each measuring point with an attribute, which makes it possible to not only measure topography, but also connect this data to the distribution of plant species, rocks, erosion gullies and other features of interest.

The threedimensional data is stored either within an internal memory or a compact flash card. With the office software "Leica Geo Office (LGO)", data may be exchanged between the instrument and a PC and exported in a wide range of ASCII formats.

The accuracy of the measurements is high; when handled correctly, the accuracy of angle measurement in this tachymeter type meets 0.3 mgon which corresponds to 0.5 mm deviation on 100 m. Concerning distance measurements, the accuracy achieves 2 mm + 2 ppm or 4 mm on 1000 m, respectively (Leica, 2007a).

2.2.5 Determination of Gravimetric Water Content (GWC) after Rain Events

On selected D4-units on the Soebatsfontein and Gellap Ost Observatories, it was possible to determine the water content of topsoils directly after a rain event. For this purpose, samples of the defined volume were taken with short core samplers, immediately wrapped into plastic bags to avoid drying, and weighed under field conditions as soon as possible. However, errors remain due to different sampling times. Sampling was only conducted after rain events, that followed longer dry periods, so that the initial water content of the soil could be regarded as negligible. Further, the sampling was conducted down to the wetting front.

After the moist weight was determined, the samples were dried. During summer this was done by putting the samples in their bags into plastic boxes with a transparent lid whose bottoms had been carpeted with black plastic folly. Temperature was controlled with a field thermometer. With this method, a minimum of 70°C was reached and samples dried for at least 5 hours. In other cases, drying under field conditions was not possible and the samples had to be exported to Germany and dried within a drying oven. Here, drying was conducted at a temperature of 105°C. To determine the error, some selected soil samples were wetted, dried at 70°C, weighed and dried further at 105°C. Deviations between the moisture content calculated after drying at 70 °C and 105 °C ranged between 0.1 and 0.3 percent and were therefore regarded as negligible.

The gravimetric water content was calculated in mm instead of percent by weight since this measure facilitates a comparison with the amount of rainfall.

2.2.6 Single Ring Infiltration

A plastic ring of 14 cm in diameter of 14 cm, a height of 15 cm and an attached cm-scale was placed on a planar area of the topsoil unit to be tested. If present, coarse sand particles around the ring were removed by using a hand brush or were blown away. Afterwards, the surface was slightly moistened with a water sprayer.

Gypsum or crack filler was used to fix the ring on the prepared soil surface. Water was carefully filled into the ring by using a plastic foly to avoid slaking. The filling height depended on the infiltration rate and was based on experience. In general, the tests should have been comparable regarding filling height (zones of constant infiltration rate of the different tests should have more or less the same ponding height). The height of the water column should be rather small because it had an influence on the infiltration rate, even if to a minor degree.

In defined intervals, the water level was read using the scale and noted down. The test was normally run on seven spots within one soil unit.

The test proved fairly applicable on Gellap and Nabaos, but had some restrictions on the Soebatsfontein study site when testing D4-units. On strongly sloped areas such as heuweltjies, it was difficult to find enough suitable test sites with a rather smooth and planar surface. At times, a compromise was reached by extending the test area beyond the range of the actual study site but without disposting into next units. Also, the D4-unit "plant canopy" could not be tested in most cases since the dwarf shrubs were on the one hand too small, to allow to place the ring below its crown, and on the other hand too large, to impose it on them. However, despite these difficulties infiltration rates could be determined on 15 D4-units on Soebatsfontein (Chapter 4.4.11).

2.3 Laboratory Methods

All soil samples were analysed with regard to the BIOTA standard procedure (Tab. 2.1) which comprised the analysis of

- pH-Value in H_2O and $CaCl_2$-extract
- electrical conductivity
- organic and inorganic carbon
- total N
- total element contents[1]

Selected soil samples were additionally analysed for

- exchangeable cations
- plant available K and P
- texture analysis

Tab. 2.1: BIOTA laboratory methods for the standard analysis of soils

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	For fine earth: with MUNSELL SOIL COLOR CHART, on wet and dry material	Munsell 2000

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[1] for samples taken in 2006 this data is missing due to a breakdown of the XRF-analysator. It is planned to still conduct the analysis, however, for this work the data was unavailable. Affected are 45 samples on Soebatsfontein (three D4-units below plant canopies) and all samples on Nabaos

Laboratory Methods

Parameter	*Description*	*Reference*
pH-value	Preparation of two soil suspensions by addition of aqua demin 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
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 oxidised 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	-

Parameter	*Description*	*Reference*
Particle size distribution (PSD)	With a dried sample of fine earth a pre-test on the PSD is conducted: if the overstanding water of a soil/ water suspension is clear, the analysis is done only acc. to a). All other samples are analysed 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 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) 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 sizes < 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 $\oslash$ 20 mm and pressed with 200 kN into a tablet. The tablet is inserted into a X-Ray fluorescence spectrometer (Phillipps PW-1404). The total concentration of the elements Al, Ba, Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Si, Sr, Ti and Zn is determined by X-Ray spectroscopy.	KIKKERT (1983)

Parameter	*Description*	*Reference*
Exchangeable cations and cation exchange capacity (CEC)	The exchangeabel 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.	-
ammonium acetate-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 of 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)

References of Tab. 2.1

Abbreviation	*Reference*
HdB	Alaily, F. (2000): Carbonate und Salze. In: Handbuch der Bodenkunde. Ecomed Verlag, Chapter 2.1.5.5
ISO 10390	Deutsches Institut für Normierung e.V. (DIN) (2005): DIN ISO 10390: Boden-pH Wert. In: Handbuch der Bodenuntersuchung, Abschnitt 3.5.1a. Wiley-VCH Weihnheim, Beuth Verlag
ISO 13878	Deutsches Institut für Normierung e.V. (DIN) (1998): DIN ISO 13878: Boden-Gesamtstickstoff, Verbrennung. In: Handbuch der Bodenuntersuchung, Abschnitt 3.4.1.58a. Wiley-VCH Weihnheim, Beuth Verlag
MUNSELL	UNITED STATES DEPARTMENT OF AGRICULTURE (ED) (2000): Munsell Soil Color Charts. New York, Gretag Macbeth
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 rsources. World Soil Resources Report 84, Rome. 88 pp.
Blake (1965):	Blake, G. R. (1965): Bulk density. 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 & Sparks (1996):	Helmke, P. A. & Sparks, D. L. (1996): Alkali Metal Properties. In: Bartels, J. M. (Ed.): Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, Inc., Madison, Wisconsin. pp. 551
Kikkert (1982):	Kikkert, J. (1982): Practical geochemical analysis of variable composition using X-ray fluorescence spectrometer. Spectrochimica Acta Vol. 38 b, No 5/6, pp. 809 - 820, 1983

Texture Classes All statements concerning particle size distribution refer to the German texture classification (Ad-Hoc-Arbeitsgruppe Boden, 2005). This classification defines the following fractions of fine earth (particles < 2 mm) with regard to particle sizes:

fraction	sub-fraction	shortform	diameter in µm	diameter in mm
clay		C	< 2.0	< 0.002
silt		Si	2 to < 63	0.002 to < 0.063
	fine silt	fSi	2 to < 6.3	0.002 to < 0.0063
	medium silt	mSi	6.3 to < 20	0.0063 to < 0.02
	coarse silt	cSi	20 to < 63	0.02 to < 0.063
sand		S	63 to < 2000	0.063 to < 2.0
	fine sand	fS	63 to < 200	0.063 to < 0.2
	finest fine sand	ffS	63 to < 125	0.063 to < 0.125
	coarse fine sand	cfS	125 to < 200	0.125 to < 0.2
	medium sand	mS	200 to < 630	0.2 to < 0.63
	coarse sand	cS	630 to < 2000	0.63 to < 2.0

Tab. 2.3: Overview on texture classes

2.4 Statistical Methods

2.4.1 Analysis of Variance (ANOVA)

General Information and Application Within this work data sets are arranged in a way that each soil sample has been analysed with regard to different parameters or dependant variables (e.g. pH, organic carbon) of which each value can be referred to a certain sampling depth and four nested scales. The different scales and the sampling depths are in statistical terms referred to as independent variables or *factors* (D1, D2, D3, D4 and Layer). These are in turn subdivided into *levels* (e.g. D4 in the levels biological soil crust, open soil, plant canopy and dead shrub; the sampling depth into layer 0-1 cm, 1-5 cm, 5-10 cm).

To find a pattern in data sets that are this complex, Analysis of Variance (ANOVA) is a suitable tool since this statistical method allows the simultaneous control of several independent factors. Different forms of ANOVA exist; in a so-called one-way ANOVA, several levels of the same factor are compared. If the effects and interaction of more than one factor are to be tested, a two-way ANOVA including two factors or a multiple factorial ANOVA including more than two factors are applicable.

Generally, ANOVA comprises two analysis steps: the partitioning of square sums and significance tests (F-tests). While the former is not subjected to any restrictions, ANOVA postulates certain assumptions for the F-test to ensure sound results and data interpretations. These comprise

- independence of variables
- normality of data sets
- variance homogeneity

Further, a two-way or multiple factorial ANOVA may only be applied if all factors and levels are combinable with each other.

The restrictions provoke some problems for the application of ANOVA on the data set in focus. In many cases, normality of the data set is not given and data distributions were identified as bimodal, skewed or exponential (see 4.6). Yet, indications are given that the F-test may still lead to a valid result: according to varying studies summarised in Bortz (2005), the normality assumption may be disregarded as long as variance homogeneity is valid. As a rule of thumb, variance homogeneity may be accepted as long as the ratio of the largest group variance to the smallest group variance is not exceeding 1.5. Further, ANOVA is even regarded by some authors as robust against the violation of the homogeneity assumption, when the sample sizes of the groups are equal. However, no strong evidence has been found in literature that would secure an application of the F-test to the data sets of this study. Therefore, additional nonparametric U-tests were conducted to draw conclusions on significant differences between groups. For the explanation of variance and hence the identification of patterns within the data sets, the square sum partitioning within ANOVA was deemed an appropriate modus operandi.

Another problem that required adaption was the postulation of a free combination of factors. In the present study, not every D4 unit had been sampled within each D3 unit, nor each D3 unit for each D2 unit since not all subunits existed within a superior group and because only the most significant units were chosen for sampling to keep the sampling amount processable; therefore, only parts of the whole data set could be analysed in this manner and it was sometimes necessary to merge the factors D3 and D2-scale into the factor ”site”. Yet, where the application of a two- or three-way ANOVA was possible, this yielded the advantage of not only analysing *main effects* such as the contribution of e.g. D4 or D3-groups on the total variance, but also the *interdependencies* between factors (e.g. contribution of the integrative effect of D4*D3-units on the total variance or in other words: D3-dependent variability of D4-units).

Basic Principle of Square Sum Partitioning In a one-factorial data set, the data is divided into groups by one factor, e.g. D4-unit, into the three levels biocrust, open soil and shrub canopy. For each group n = five samples of the first cm of soil are given. The independent variable may be organic carbon content.

In a first step, the square sum of the total data set is calculated as the sum of squared deviations of each single value from the total mean:

$$SS_{tot} = \sum_{i=1}^{n} \sum_{m=1}^{n} (x_{mi} - \overline{T})^2 \tag{2.1}$$

with SS$_{tot}$ = square sum of the total data set, i = index of factor levels, n = number of values m = index of values within factor levels, $\overline{T}$ = mean of total data set and x = value,

In a next step, it should be determined how much the factor D4 contributes to the variability within the total data set. If the three factor levels were the only variance generating sources, all values within the same level would be the same. However, in reality, this is not the case. To estimate the contribution of the levels (e.g: BSC) to overall variability, the ideal assumption is approached by exchanging the single values with the mean of the level, which is regarded as the best estimation for the effect of the three levels on the parameter. When the square sums of the level are summed up, the square sum of the factor is derived:

$$SS_{fac} = n \sum_{i=1}^{n} (\overline{A}_i - \overline{T})^2 \tag{2.2}$$

with SS$_{fac}$ = square sum of factor, n = number of values, i = index of factor levels, $\overline{A}$ = mean of level a and $\overline{T}$ = mean of total data set.

As a last step, the so-called error or residual variance is calculated. The part of the total variance that is based on the D4-units is substituted by a residual part of variance that is independent of the regarded factor D4 and may be referred to other variables such as microtopography, distance to plants, location on or next to former plants and so on. To determine the contribution of the residual variance on total variance, the degree of difference of values within a group is calculated. This is achieved by calculating the difference of the individual value from the level group mean and squaring the result. Thus, an error variance for each level is calculated. Summing up the residual square sums of the three levels results into the residual square sum of the factor:

$$SS_{res} = \sum_{i=1}^{n} \sum_{m=1}^{n} (x_{mi} - \overline{A})^2 \tag{2.3}$$

with SS$_{res}$ = square sum of residual variance, i = index of factor levels, n = number of values, x = value, m = index of values within factor levels, $\overline{A}$ = mean of level and $\overline{T}$ = mean of total data set.

In the end, ANOVA delivers the following data:

- SS_{tot} = variance of the total data set
- SS_{fac} = variance of the groups within the whole data set
- SS_{res} = residual variance that is to be explained by other factors then those being included into the analysis.

SS_{fac} and SS_{res} sum up to SS_{tot}. The three values can be used for explanation of variance in the whole data set.

Although the significance test within ANOVA is disregarded within this study, its basic principle should be briefly mentioned here as well: by dividing the square sums through the degrees of freedom, the variance is derived. In accordance with the standard error of the mean, under the null hypothesis, group variance is a good estimation of the residual variance. Based on this assumption, F is calculated as ratio of the two:

$$F = Var_{fac}/Var_{res} \tag{2.4}$$

with Var_{fac} = factor variance and Varres = residual variance

F is then compared with an empirically determined F_{crit}-value considering the degrees of freedom and the set probability error. Depending on F being larger or smaller than F_{crit}, the null hypothesis or the alternative hypothesis are accepted.

Square sum partitioning in multifactorial ANOVAs Multifactorial ANOVAs allow to assess the contribution of several factors on the total variability simultaneously. As in the one-way ANOVA, square sums and residual variances of the different factors are calculated, but moreover the interactions between the factors are also determined. As an example for the present study, a two-way ANOVA would be the appropriate method to reveal that organic carbon content is increased below plant canopies compared to open soil, but only in the layer 0-1 cm. Thus, it can be concluded that the factor D4 (differentiation into open soil and plant canopies) may have a layer-depending effect on organic carbon content.

In the following, a summary of the principle will be provided here by using the above-mentioned example of a two-factorial ANOVA. For a detailed description of the single calculation steps and further reading, Bortz (2005) is suggested.

As in the one-way ANOVA, the total square sum of the complete data set is determined. This value reflects the variability of all values.

Hereafter, the data set is modified in a way that assumes that all variability is generated exclusively by the two factors by mean differences between their corresponding levels. In the one-way ANOVA, the mean of the data within each level was regarded as an estimation for the factor effect on variability. Here, the same is done but instead of the mean of each level, the means of so-called cells are used. A cell comprises all values that have the same factor combination. According to the above mentioned example with the factors D4 and Layer, one cell would e.g. consist of values that can be referred to both, open soil and sampling layer 0-1 cm.

Analogues to one-way ANOVA, the single values are exchanged with the corresponding cell means and with this modified data base square sums are calculated again. The result is a square sum that envelopes the two factors involved. The square sum of residual variance is derived by calculating the difference of individual values from the cell mean and squaring the result.

As a next step, the square sum of the two factors is calculated separately as in equation 2.2. No difference exists in terms of modus operandi in the one-way ANOVA. Considering that no interactions as described above occur in the data set, the sum of two factor square sums would equal the cell square sum. However, this must not necessarily be the case: sometimes the sum of the factor square sums is less than the cell square sum. From such a phenomenon it must be concluded that a variability component exists which is neither explainable by the levels of factor A (differentiation into plant canopy and open soil) nor by levels of factor B (varying sampling depths) alone, but by their combination.

For the determination of these interactions, the individual values are substituted by empirical determined cell means. These values are compared with an expected mean that would occur if only the two factors are exhibiting an effect on variability in the data set. The derived square sum is called square sum of interaction.

On summary, in a multiple factorial ANOVA, the following square sums are obtained:

- square sums of the single factors
- square sum of the residual variance
- square sum of the varying interactions
- total square sum.

The square sums of the single factors, residual variance and interactions sum up to the total square sum. When multifactorial ANOVAs are applied by statistical programs such as SPSS, these square sums are listed in a table with their corresponding variances, F-values and significances. In addition, it was of interest in this study to compare the square sums of the individual levels as a measure of variability that is based on particular environmental units such as patches of biological soil crusts.

2.4.2 Mann-Whitney U test

The Mann-Whitney U test is a non-parametric test that assesses whether two independent groups (A, B) have been drawn from the same population. The null hypothesis H0 implies that the two sample groups have the same distribution and therefore belong to the same population.

In a first step, the observations made within both groups are combined and ranked in order of increasing size. If H0 is correct, it would be expected that each sample of one group would ideally follow one sample of the other, for example in the order *ababababa*. An order slightly deviating from this rank such as *ababaabab* would be accepted to verify H0, since it is highly probable that such an order developed randomly although the two groups belong to the same population. If the order is strongly divided into the two groups such as *aaaaabbbb*, it is assumed improbable to be random which leads to a rejection of H0. In other words, the alternative hypothesis H1 is accepted when the probability that a score from A is larger than a score from B is greater than one-half or

$p\ (A > B) > 0.5$

Practically, U is determined by the calculation of the number of how often a sample of one group precedes a sample of the other within the rank. The probability of obtaining a given U in a group of n A's and m B's is the solution of a certain recurrence relation involving n and m. Recurrence tables have been computed to give the probability of U for groups up to $n = m = 8$. At this point the distribution is almost normal, therefore for samples above 20 there is a good approximation using the normal distribution.

If the null hypothesis has a direction (for instance, BSCs raise the pH value of topsoil in comparison to matrix soil), a one-tailed test is applied. Here, it is tested, whether $A > B$ or $A < B$. In a two-tailed test, H0 is accepted when $A = B$. Since all data values are ordered in ranks, the U-test is robust against extreme values (Mann & Whitney, 1947; Siegel, 1956).

2.4.3 Cluster Analysis

Cluster analysis is an exploratory analysis tool that serves the purpose of sorting different objects into groups in a way that differences within a cluster are minimal and differences between clusters are maximal. For this work, a hierarchical cluster analysis (HCA) was applied. Within this method, each object is regarded initially as one individual cluster. In a second step, a pairwise distance is calculated between all objects and those with the smallest distance are merged to one cluster. With that procedure, the number of clusters is reduced by one. Subsequently, the remaining n-1 clusters are again compared and those with the minimal distances combined to one cluster. With every step the number of clusters is reduced by one until all objects are merged.

Distance is the basic criterion for any clustering. After each aggregation, the definitions of distances between the single objects and clusters have to be defined anew. For this purpose several methods can be applied. In the *single linkage*-procedure (SPSS: "nearest neighbour"), the distance between two clusters is determined by the pair of nearest objects between clusters. In the procedure *complete linkage* (SPSS: "furthest neighbour"), the opposite is the case and the distance of two clusters is determined as the maximal distance of two objects of each cluster. In the procedure *average linkage* (SPSS: between-group linkage) used in this work, the distance of two clusters is determined as the mean of the distances between all pairs of objects.

As a measure of similarity or distance, respectively, the squared Euclidean Distance was selected. This is calculated as:

$$\sum_{i=1}^{n}(x_i - y_i)^2$$

or in other words the sum across variables (from i = 1 to n) of the squared difference between the score on variable i for the one case (Xi) and the score on variable i for the other case (Yi). In addition, a z-standardisation was applied to the data set before conducting the cluster analysis to equalise the effect of variables measured on different scales. By doing this, SPSS standardised all of the variables to mean = 0 and variance = 1.

The cluster solution was graphically summarised in a dendrogramm, a diagram that lists cases or objects in a column on the left linked by a classification tree. On top, a horizontal axis depicts the distance between clusters when they are joined (Wiedenbeck & Züll, 2001; Bortz, 2005).

2.4.4 Box-and-Whisker Diagrams

For graphical illustration of results in this work, often Box-and-Whisker diagrams were used such as in Fig. 2.2. These diagrams indicate the following statistical measures: boxes: interquartile range which contains 50% of values; whiskers: highest and lowest values < 1.5 times the box length; circles: min/ max values > 1.5 times the length of box. The line through the boxes (here missing) depicts the median. Alternatively, mean values are depicted by asterisks.

2.4.5 Standardisation procedures

One focus of this work was to analyse the effect of D4-units such as biologically encrusted or plant canopy areas on topsoils. For this purpose, the open soil unit was regarded as control unit and compared to the data of another D4-unit within the same D3-unit. For such analysis several data pairs were used and it occured by times that all, independent of their affiliation to superior scales in the hierarchical system, showed

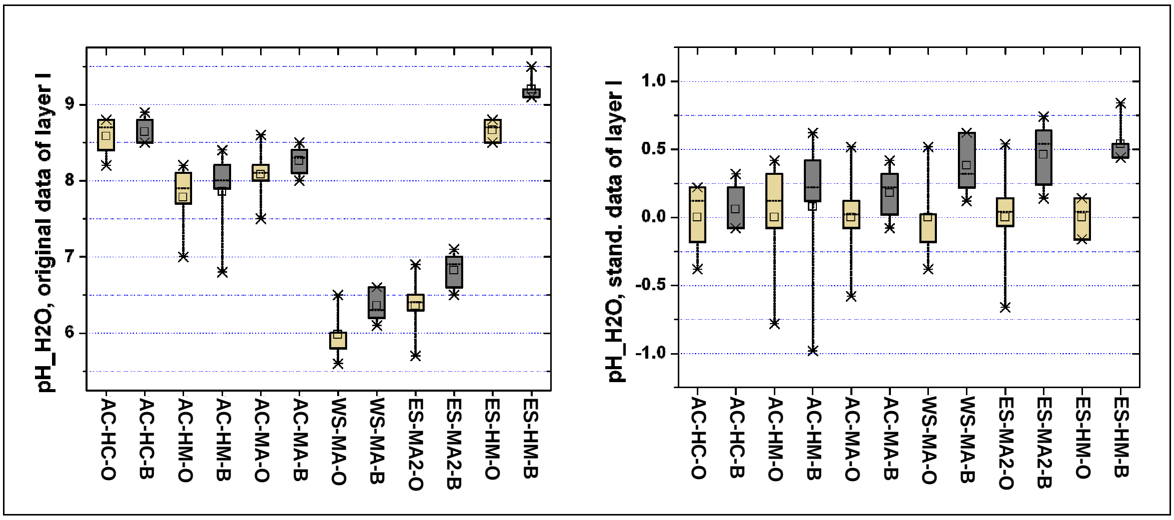

Fig. 2.2: Example for the standardisation of the data pairs with regard to pH$_{H2O}$: brown boxes represent Open Soil, grey boxes BSC data. On the left: original data distribution; on the right: after standardisation. Site abbreviations see Tab. 4.1.

the same trend. This was for instance the case in the comparison of open soil with biologically encrusted soil as shown in Fig. 2.2, where in five of six cases the pH-value was increased on crusted sites. Often, the observed trends were only small and not statistically confirmable when only regarding single data pairs due to small sample numbers of n = 5 for each D4-unit and layer. Therefore, a procedure was conducted to analyse such effects in a combined data set after the site-specific differences were eliminated by standardisation.

A standardisation of the data was achieved by calculating the mean of the 5 samples of particular layers of the open soil part of each pair and subtracting that mean from each value from both, open soil and biocrusted data set. Thus, the relation of the BSC-data to the open soil data of each data pair remained the same, while the mean of each open soil data distribution was fixed to the value zero. Fig. 2.2 shows the data before and after the standardisation procedure was conducted.

2.4.6 A Note on D3-Variability Analysis in Soebatsfontein

During the analysis of D3-variability in Soebatsfontein (Chapter 4.4.2.3), a complicacy was met in terms of the comparability of D3-units. Fig. 2.3 shows exemplary D3-variability for the parameter pH$_{H2O}$. Since sampling was undertaken with regard to selected D4-scale, each D3-unit consists of several D4-units, presented as single box-plots. Since nature varies the composition of patterns in different habitats, D3-data sets consist of varying compositions of D4-units. Also, due to data processing purposes only the most significant D4-units were sampled which already led to a total of 495 soil samples and an approx. data base of 16,000 single values for Soebatsfontein. Comparisons between Matrix D3-units and Heuweltjie-units for instance may be therefore based on a different composition of the comparative data sets in terms of D4-consideration.

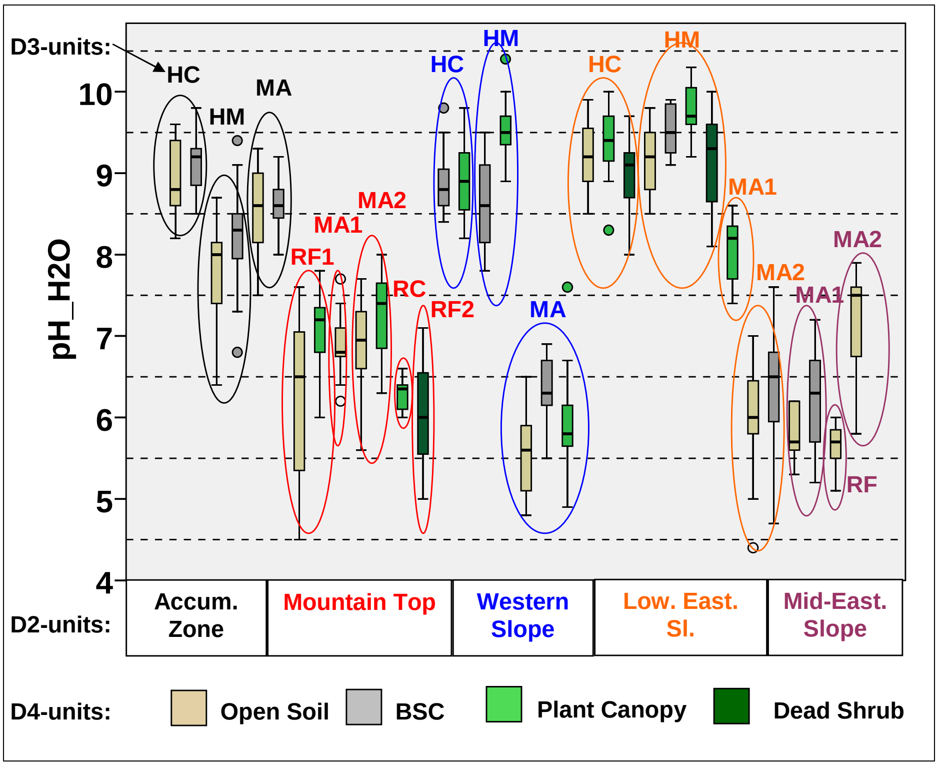

Fig. 2.3: Diagram visualising D4-unit composition of the D3-units sampled in Soebatsfontein: exemplary for the distribution of pH$_{H2O}$-values depicted as boxplots.

The author is aware of this constraint but decided to nevertheless conduct U tests on these D3-groupings. D4-contents of the present D3-units are regarded as main drivers of variability, thus justifying statistical comparisons without taking areal contribution into account. If emphasising the areal representativeness of single D4-units under assumption of exclusive occurrence of the sampled units, a mean may be derived by weighting the data in accordance to areal distribution, but in this case no statistical tests may be applicable due to the lacking sample number. However, the significance of D4-units on soil properties will be specifically analysed in chapters 4.4.3 and 4.4.5.

2.5 Soil Classification

Since the bulk of soil data was derived from topsoils only, a classification of soils was only required for the reference profiles specified in the Appendix (A.1 and B.1). These were classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006) which is in accordance with the BIOTA standard procedure of soil classification. A detailed explanation regarding the preference of this classification over other systems such as the USDA Soil Taxonomy (Soil Survey Staff, 2006) is provided in Petersen (2008).

2.6 Software

The statistical analysis was predominantly conducted with SPSS 15.0 for Windows, in individual cases Origin 7.5G was used. Survey points were processed to digital elevation models (DEMs) with ArcGIS 9 software. The dissertation itself was compiled with LaTeX.

2.7 Satellite Data and GPS-Coordinates

Satellite picture data for digital elevation models was derived from Google Earth©. Coordinates of the hectare plots within the observatories were derived from initial DGPS surveys of all BIOTA observatories by a private company. Reference points of small scale study sites taken in the field were obtained from GPS readings (Garmin 12, III+, 60).

3 Literature Review

3.1 Analysing the Scale Dependent Variability of Soils - an Introduction

Soil is a three dimensional body, whose composition is the result of the soil forming factors parent material, climate, topography, biota, time and anthropogenic use (Jenny, 1941). The soil genesis factors lead to manifold soil forming processes that in turn result in soil properties that vary widely in space and time. Since soil is a continuum rather than a single entity with a fixed set of attributes (Ibáñez & Boixadera, 2002), the scale dependent heterogeneity of soil properties is considered problematic with regard to appropriate sampling strategies and quality of information (McBratney, 1992). Yet its characterisation is essential to achieve a better understanding of complex relations between soil, environmental factors and land-use systems (Ibáñez *et al.*, 1995; Yemefack *et al.*, 2005).

There are basically three ways of describing the qualitative and quantitative properties of soils in a given area: by taxonomy, by using classical statistics and by applying geostatistics. *Taxonomic variability* or *pedodiversity* is expressed by the diversity of soil classes in any soil classification system (McBratney, 1995). However, the underlying conditions that lead to the definition of soil types and classes may vary and are summarised by Lamp (1972) and Kneib (1989): morphogenetic systems such as the German soil classification (Ad-Hoc-Arbeitsgruppe Boden, 2005) were derived from the assumption that particular environmental factors lead to soil forming processes that exhibit a characteristic composition of properties over time. Soils with the same profile morphology and similar attributes are interpreted as soil types or classes with the same genesis. Other systems are based on pragmatic-empirical approaches: classes are defined by diagnostic horizons with fixed ranges of specified soil properties. An example for this classification is the American Soil Taxonomy (Soil Survey Staff, 2006). Most of the modern classifications are combined systems, for instance the international World Reference Base for Soil Resources (IUSS Working Group WRB, 2006) that originated in the legend description of the FAO's soil map of the world (FAO-UNESCO, 1971-1981). The revised version distinguishes between 32 main soil groups that may be attributed with 179 soil units in the next lower order. For the identification of soil units, 39 diagnostic horizons and 14 diagnostic properties are defined by qualitative and semiquantitative properties and intervals of physical and physicochemical values. The binomial South African Classification System (Soil Classification Working Group, 1991) is based on profound survey information and uses combinations of topsoil and subsoil horizons to assign a soil to a specific soil form. As a next step, further properties lead to the determination of predefined soil series.

The classification of soils according to one of the classification systems are usually needed and used for soil surveys and the creation of maps. Depending on the required information, soil maps may be scaled differently. A map on the farming scale for instance is a helpful tool for agricultural purposes. Difficulties of extrapolation from point to area information exist due to the above-mentioned fact that soils change continually in space and time. Hence, boundary delineation of mapping units is a matter of prediction and may contain errors. The continuum issue was approached by hierarchical models of soil associations as summarised by Schmidt (1996): In this concept, as a first step soil bodies have to be described that hold all attributes of the soil to be classified such as particular horizons and substrate layers as well as their spatial configuration. This soil body is the basic unit for classification and is referred to as pedon. The size of a pedon may vary between 1 to 1000 m^2. While the pedon concept is sufficient for taxonomic purposes where soils are classified according to their property combinations in nested hierarchical units, soil geography postulates its link to space to describe a pedons distribution in a landscape. Therefore, soil geographers work with so-called polypedons as basic units that are defined as the distribution areas of specific pedons. Further, different polypedons may be merged to pedotops. In contrast to the polypedon, pedotops are not strictly homogenous in the sense of encompassing areas of only one pedon; they rather include embeddings of adjacent or even stronger deviating polypedons and allow edge effects. They may be regarded as "flawed" polypedons and represent the actual basic unit of soil mapping. Higher hierarchical units encompass the regular structure of several soil units with regard to overarching landscape factors such as relief and groundwater (choric dimension), similar tendencies of soil development in even larger areas (regional dimension) and on global scales (zonal or geospheric dimension).

By use of a map with soil classes, statements can be made regarding the pedodiversity of different areas and thus regarding the quality of rangelands, the persistence of an ecosystem and so on. As presented exemplary by McBratney (1995), different areas of the same size may be ranked according to the number of different classes, the relative number of classes or the interfacial length of classes with one another, all measures of taxonomic diversity. But is the pedon, the lowest mapping unit and the starting point of a soil map, sufficient to characterise an area of the size of a polypedon? Or is there a variability of soil properties on the finer scale beyond the mapping unit that significantly influences ecological interactions that are not detectable through mapping on pedon scales? Obviously there is one. Miehlich (1976) regards soils as natural bodies that are inhomogenous per se and also suggests to use the term *variability* for this inherent property of soils. He concludes from this attribute that "it is not very meaningful to test for homogeneity, but rather to quantify the extent of inhomogeneity" to compare and describe soils. In doing so, he proposes to evaluate variability of soils by comparing the coefficient of variability of different soil bodies, either of one or several parameters. Further, Miehlich shows that variability is a matter of scale and whether a soil - or to be more precise, a sample volume - may be regarded as homogeneous or inhomogeneous is a matter of perspective. Based on his considerations on the deviation from the ideal statistical arrangement (AviA), he derived a concept of superimposed pattern complexes in which partial units of a soil body may cluster with respect to their local connection to larger units that vary less within than between each other. The areas of similarity in turn may be regarded as one homogenous unit that differs from other clusters of a comparable volume. An example is given that describes the pattern development of pedogenic iron from μm^3 to m^3 scale.

Göttlein & Stanjek (1996) analysed the micro-scale heterogeneity of different parameters of soil solution and soil solid phase in a cambic podzol profile. As a result, they found out that spatial distributions of two parameters (pH and sulphate) did not correlate with soil horizon borders. Mills & Fey (2004c) and Fey *et al.* (2006) constituted the concept of the *pedoderm* for arid and semi-arid environments signifying "the thin layer of soil at the interface with the atmosphere, a few millimetres to centimetres thick, within which certain properties exhibit a marked vertical change in expression sometimes not readily detected through field observation" (Fey *et al.*, 2006). Cheng *et al.* (2004) highlight the importance of micro-scale heterogeneity of soil properties in semi-arid and arid landscapes, especially when degraded, and the fact that only few studies have focused on that topic. These all give a strong indication that in semi-arid environments investigations should not exclusively be conducted in pedon or polypedon units, but also on single soil properties, on even smaller scales and uncoupled from horizon borders to further improve the understanding of ecosystem processes.

This *variability of soil properties* may be described by measures and tests of classical statistics such as variance (S^2), standard deviation (SD), coefficient of variation (CV), range and quartile (Lozán & Kausch, 1998; Webster & Oliver, 1990; Ehrenberg, 1986). Basic requirement is the definition of a main unit or the scale of examination, respectively. As proposed by Miehlich (1976), for soil scientific observations a scale must be defined in which soil units are regarded as homogenous and a further differentiation must be neglected. Instead of homogeneity, the author proposes the term *equality* of a soil body if its "inhomogeneity does not exceed a preset limit specific to the objectives of the investigation". The description of soil variability with classical statistics regards single parameters and aims to identify interactions between them. The approach to integrate several parameters on a predefined scale to form units with the same set of properties is called *parametric pedodiversity* and requires the application of complex statistical tools (Petersen, 2008).

However, the adequate description of soils either in the sense of taxonomic pedodiversity or parametric variability remains an issue. Therefore, a specific branch of soil science developed, pedometrics, that seeks to solve the continuum problem from the mathematical angle. This subject is defined as "the application of mathematical and statistical methods for the study of the distribution and genesis of soils" (Heuvelink, 2003) and aims to create tools that help to improve classification and mapping of soils on the one hand side and to understand and predict pedodiversity on the other (Yaalon, 2003). In this field of research, often *geostatistics* are used, a discipline of classical statistics that was developed in the 1970ies for mining purposes, mainly by G. Matheron as reviewed in Akin & Siemes (1988). Journel (1986) defines geostatistics as a branch of statistics specialising in the analysis and modelling of spatial variability in earth sciences. According to Webster & Oliver (1990), geostatistics enables the researcher "to predict the values of properties from those of others and to estimate the values at unsampled places or larger areas from values measured at the sampling sites". Geostatistical methods postulate specific sampling schemes (Webster & Oliver,

2001) whereas in classical statistics, values of different sampling places are treated as though they were spatially uncorrelated (Di *et al.*, 1989).

Ibáñez & de Alba (1999) distinguish explicitly between the spatial variability of soil properties and soil taxa. They suggest an assessment of taxonomic pedodiversity by diversity indices and distribution models, while variability of soil properties may be analysed and described by means of geostatistical tools. Moreover, Saldaña & Ibáñez (2004) could show that pedodiversity derived of taxonomic units obtained different results on terraces of the Henares River in Spain than soil variability that had earlier been analysed on the same sites with geostatistical tools by Saldaña *et al.* (1998). Some research activities aim at the combination of taxonomic and parametric pedodiversity to achieve soil maps with better informative values, for instance for GIS applications, in the modelling of water flow and contaminant transport and environmental impact assessment. Rogowski & Wolf (1994) combined soil survey attributes and kriged overlays of measured data of the parameters bulk density and hydraulic conductivity. By doing this, they achieved a soil map that includes aspects of the attribute continuity and the variability from geostatistical analysis.

In accordance with Ibáñez & de Alba (1999), this work distinguishes between the classificatory approach and the analysis of the variability of soil properties. A soil classification on observatory basis conducted by Petersen (2008) is used as a basis data set for finer scaled studies with focus on the variability of mainly topsoil properties and their mutual dependencies with biota and topography. The resulting description of soil and vegetation patterns, the derivation of eco-functions and identification of processes in those semi-arid environments might be regarded as a supplementary research to the pedological approach that will lead to a better understanding of arid and semi-arid ecosystems. Since the investigations described here were conducted on a scale ranging from cm^2 to ha-size and are thus of finer resolution than on the observatory scale (1 km^2), they are in the following referred to as small scale observations in line with habitual language use.

3.2 Understanding the Significance of Scale

It is agreed by several authors that in ecology the question of scale is a fundamental issue for research purposes, connecting population biology and ecosystems science as well as basic and applied ecology (Levin, 1992; Ludwig *et al.*, 2000; Wiens, 1989). The concepts of scale and pattern are closely linked (Hutchinson, 1953); the identification of pattern is the key to the identification of scales (Powell, 1989), and both are the entrée to predictions and ecological models that are required for the development of sustainable management practices in arid and semi-arid ecosystems (Ludwig & Tongway, 1995; Ludwig *et al.*, 1999).

Each ecosystem features a number of species of which each experiences its environment on a range of scales leading to a complexity of processes, patterns and functional interactions. Scaling properties differ among different kinds of organisms, different kinds of environments, and time periods (Ludwig *et al.*, 2000). Van de Koppel *et al.* (2005) describe this as the ”functional range of a consumer”, which is the scale range defined by habitat size and observational window (”grain”) at which a consumer experiences his habitat. The influence of this functional range is expressed, for instance, with ignoring fine-scale patches such as a single tussock on a bare patch by an ungulate due to the costs associated with the interruption of movement. As a consequence, resources are protected against consumption in fine-scale patches.

The fact that multi-scaled process studies are still in their infancy (Ibáñez *et al.*, 2005) and recent modelling methodologies do not explicitly take scale differences into account (Wilcox *et al.*, 2003) are weighed against the pressing need for action in terms of agricultural productivity for a growing human population and simultaneously development of conservation and restoration measures. But the scale of scientific observation to improve the understanding of ecosystem dynamics naturally establishes a perceptual bias: processes and interactions are regarded through a ”window” (the scale) in a timely snapshot that may vary significantly, for instance between wet and dry seasons; thus, timely and spatial scale of observations determine which patterns and processes are detected and which are missed (Ludwig *et al.*, 2000). The observed variability of a system will always be conditional on the scale of description as will be the evaluation whether an apparent equilibrium or non-equilibrium is perceived; Wiens (1989) emphasises the role of system openness. At the scale of individual habitat patches in a landscape, for example, mosaic population dynamics may be influenced by between-patch dispersal, but at the broader scale of an island containing that landscape, emigration may not occur and the population closes. The same island, however, may be open with regard to atmospheric flows or broad scale climatic influences. Therefore, it is a function of the system openness whether the investigations made concerning a system at a particular scale will reveal something about ecological mechanisms.

By changing the scale of description, a researcher moves from unpredictable, unrepeatable individual cases to groups of cases whose behaviour is regular enough to allow generalisation. In so doing, the benefit of gaining predictability is bought with the loss of detail or heterogeneity (Levin, 1992), and the enhanced ability to detect broad-scale patterns is associated with a loss of resolution of fine-scale details (Wiens, 1989). That may be the reason why a lot of previous and recent publications focus on ecosystem studies on particular scales without accentuating the consequences for other scales in particular. Those studies range from rhizosphere interaction to landscape modelling via remote sensing, from small to global scale.

However, processes that might start on a small scale might be the initial trigger for changes on the landscape, or even larger scales. Belnap *et al.* (2003) concentrate on the role of small scale boundaries in arid and semiarid ecosystems. They distinguish two kinds of boundaries: the interface between atmosphere and soil surface and the transition between bulk soil and plant roots. The consequences of small scale interactions can be highlighted by the function of biological soil crusts that largely pose the boundary between atmosphere and soil in arid ecosystems. Apart from the effects on local hydrology and soil properties, biological soil crusts are capable of nitrogen fixation and therefore contribute significantly to the N availability in the otherwise N-limited semi-arid terrestrial ecosystems. This example shows that although the scale of these boundaries is relatively small, their integrated impact can be important at landscape scale. Further considerations even encompass its impact on global scales: if anaerobic micro-sites occur that are associated with high carbon availability e.g. in rhizosphere soil, this might lead to denitrification of a substantial portion of nitrogen which then also accounts for the production of the atmospherically reactive trace gas nitrous oxide N_2O.

The awareness of the significance of scale emerged during the 80s and persists until today albeit without having solved the problem. Wiens & Milne (1989) and Levin (1992) postulated a multi-scaled perspective on landscape patterns and dynamics. Investigations of mosaic patterns should on the one hand be scaled to the actual research questions and thus to the organisms and phenomena in focus; on the other hand studies should be conducted over a range of scales to examine how far the processes observed influence the next lower or higher hierarchical system (Wiens & Milne, 1989). It was also advocated to start considerations from microlandscape approaches, and bottom-up via remote sensing and extrapolation to larger scales. However, this again poses difficulties. The scale dependencies of environment-organism relationships is not linear (Ludwig *et al.*, 2000), and applying principles developed at one scale to different scales may confront the researcher with discontinuities of scaling (Belnap *et al.*, 2003). An approach to solve this challenge is presented by Ludwig *et al.* (2000) with the hierarchical theory: domains of scale have to be identified within which functional relationships remain relatively consistent. Those may be represented as hierarchical levels. Observations should be scaled to include not only the level of interest, but also the next lower and next higher level.

For this approach, the ideas of Forman (1995) concerning land mosaics might be regarded. In his work he structures regions in landscapes in a nested way, which are on a finer scale composed of the structural patterns patches, corridors and matrix. The composition of these structures determines functional flows and movements through the landscape and changes in its pattern and process over time. From the classification of a landscape in coarse grain or fine grain sized landscapes, statements on site diversity and the tendency of species as generalists or specialists can be derived.

Cadenasso *et al.* (2003) go one step further in their framework of boundaries: the overarching goal of their considerations is the understanding of the regulation of flows across heterogeneous space. In their opinion, the research question again determines the patch and the boundary. For instance, the same estuary can be regarded as boundary between freshwater and saltwater systems for different research questions or as a patch if regarded as a nursery ground for fish. By analysing three components of the framework (flow, nature of bounded systems and nature of boundary), statements and predictions about the dynamics and persistence of spatial mosaics can be inferred. Moreover, this approach can be applied through all spatial and temporal scales.

Several groups deal with ecological-hydrological systems and process studies in semi-arid landscapes across fine to coarse scales. A lot of research work concerning this issue was conducted in Australian savannas. Ludwig & Marsden (1995) and Ludwig & Tongway (1995) described the patchiness of semi-arid landscapes as a source-sink phenomenon, where natural resources are concentrated into patches. Ludwig & Tongway (1997) and Ludwig *et al.* (2005) developed the Trigger–Transfer–Reserve–Pulse (TTRP) framework for semi-arid landscapes. They focus their research on landscapes that are structured in vegetated and non-vegetated patches, at hillslopes frequently forming vegetation bands, therefore being termed as "banded vegetation patches". According to their framework, the scale of patches may increase due to landuse and degradation until a threshold is reached and a cascade effect applies when e.g. runoff exceeds the storage capacity of patches. At this stage, landscapes may turn from conserving to leaky states. The TTRP framework was applied by Belnap *et al.* (2005) to precipitation pulses on microbial communities and microbial mediated nutrient cycles at three different scales in hot and cool deserts ranging from plant interspaces, plant island patches and hillslopes.

The generation of vegetation patterns is described as a general phenomenon in ecosystems sharing harsh abiotic conditions where plants can only survive if they facilitate their own growth by improving their micro-environment. HilleRisLambers *et al.* (2001) refer to those mechanisms as "facilitation".

But what is the ecological significance of scale dependencies?

Natural vegetation patches are the only structures in landscapes that protect aquifers and interconnected stream networks, sustain viable populations of most interior species, provide a core habitat and escape cover for most large-home-range vertebrates (Forman, 1995). Scale dependencies in hydrological response have important ecological implications (Wilcox *et al.*, 2003). Therefore, the understanding of patchiness and the role of humans in fragmenting habitats is the key to predictions on the persistence of rare species and the spread of pest species (Levin, 1992). The spatial organisation of landscapes in patches allows a coexistence of competitors (Tilman *et al.*, 1997) and consequently promotes a high degree of biodiversity and thus ecosystem stability.

The investigation of source-sink phenomena, the identification of thresholds and the formulation of scaling rules (Ludwig *et al.*, 2000) will help to develop predictive models for sustainable management. A further tool is the deduction of indices for degradation and ecosystem state. In this context Ludwig *et al.* (2002) derived and tested a directional leakiness index (DLI) for the resource retention function of a landscape. Schlesinger *et al.* (1996) suggested using comparisons of soil heterogeneity as indices of desertification.

Currently, there is a high awareness of research need in terms of scale dependent determination of processes (Scanlon *et al.*, 2007; Solé, 2007; Desmet, 2007). Some authors are contributing to this topic with recent works. Areas of research in this context are located in North America (Chihuahuan Desert and Mojave-Desert in New Mexico, Sonoran Desert in Arizona, Colorado Platea as an example for a cold desert), Australia (Mulga-woodland and Chenopode shrubland), and West Africa (Burkina Faso, Niger).

However, there is a lack of data for southern African savannas.

In addition, several authors postulate more data ranging across several scales instead of focusing on one scale (Ludwig *et al.*, 2000; Levin, 1992). Also, several publications demand more data and case studies to enable testing and elaborate current models and conceptual frameworks (Ludwig *et al.*, 2005; Tongway & Ludwig, 1997a).

3.3 Mutual Dependencies between Species (Biodiversity) and Soil Properties in Drylands

Soils, as part of the ecosystem, influence the composition and abundance of plants and animals and vice versa. Thus, biodiversity and pedodiversity are directly linked and are also affected by geology, topography, climate and anthropogenic use. In arid and semi-arid environments, small scale patchiness of soil properties and vegetation affect the distribution of water and nutrients and therefore ecosystem functions. The cause of small scale patchiness in those landscapes is manifold and in most cases due to soil-species interaction whether recent or relic. Some of the mutual dependencies with special emphasis on southern African drylands are reviewed in the following subchapters:

3.3.1 Plants

In semi-arid environments, plants are subject to extreme conditions due to climate occurrences such as scarce and unreliable rainfall and high temperatures (Went, 1948). Climate is also a factor governing soil development, in some cases leading to soil properties that might again exhibit harsh environmental conditions for plants (e. g. through salt accumulation), in others providing resources (water, nutrients, substrate for rootage) through e.g. water holding capacity that just allow plant survival. Water availability plays a key role for plants; this is shown by the fact that some desert plants produce roots that extend to 20 m and more to ensure sufficient water supply (Smith, 1968). The presence of ligneous plants has been found to be linked with higher infiltrabilities in a Sudanian fallow-land (Fournier & Planchon, 1998); Jenny *et al.* (1990) found out that additional lateral water favoured the conditions of microhabitats in the Wadi Araba in Jordan whilst sealed surfaces and gravel terraces offer less favourable conditions to diaspore establishment than sandy surfaces. Fuller (1974) and Tester & Davenport (2003) summarise the effects of salinisation by general osmotic effects, limiting plant available water, specific ion effects on inhibition of nutrition, and toxic effects by particular ions. Plant species numbers are linked to the abundance of limiting soil resources: according to Harpole & Tilman (2007) simplification of habitats by eutrophication may lead to a decrease of niche dimensionality, and thus to long-term biodiversity loss.

Vice versa, plants affect soil properties by varying strategies. Infiltration rates increased strongly with increasing vegetative cover as observed by Loch (2000) by simulated rain and overland flow in Queensland, Australia. A well-known phenomenon is the occurrence of so called "islands of fertility" that have been investigated by numerous authors (Schlesinger & Pilmanis, 1998; Schlesinger *et al.*, 1996; Johnson *et al.*, 2002; Tiedemann & Klemmedson, 1986; Klemmedson & Tiedemann, 1986; Wilson & Thompson, 2005). Early works of Tiedemann & Klemmedson (1973) and Virginia & Jarrell (1983) observed desert grassland soils under the woody, nitrogen fixing legume *Prosopis juliflora* (mesquite) and compared them to adjacent open areas. Below the plant canopies, soils were enriched in C, total N, nitrate, ammonia, P, K and S. Virginia & Jarrell (1983) refer the accumulation of nitrogen to limited leaching and denitrification due to aridity. Everett *et al.* (1986) found under singleleaf pinyon crowns in the Shoshone Mountains of west-central Nevada enhanced nutrient contents compared to interspace soil. So did Halvorson *et al.* (1997) in a cool desert in south central Washington under *Artemisia tridentata*. From their investigations on burned and unburned sites and their comparisons to locations, where shrubs were removed by fire 9 years earlier, they concluded that resource islands are generally not self perpetuating once established but appear to be dependent on a supply of inputs associated with the presence of living shrubs. Although they diminish after the removal of the plants, fertility islands are detectable as "ghost islands" for at least 10 years after removal for several parameters such as C_{org}, N_t and EC. The processes leading to fertile islands are reviewed by Hook *et al.* (1991). Organic matter is accumulated below crowns of shrubs and trees by litter fall and redistribution of topsoil material by wind and water erosion, often leading to hummocks where the soil is 2-3 cm elevated beneath individual plants relative to surrounding soil (Burke *et al.*, 1999). Additionally, nutrients are taken up by roots from inter canopy areas, then accumulated in tissues and deposited as litter beneath the plants. Dean *et al.* (1999) report of *Acacia erioloba* trees in the Kalahari as focal points for animal activity, especially concerning birds. Faeces, fallen nest material and carcass remains enhanced the N and K content by a factor of 2, P by a factor of 2.5. They further found out that species that produce fleshy fruits occurred most frequently below large *A. erioloba* trees and conclude from their findings that large trees play an important role in maintaining biodiversity through patch dynamics which cannot be achieved by homogeneous thickets of acacias that are a common feature of overgrazed sites. By contrast to Bhark & Small (2003) and Schlesinger *et al.* (1990), who see the development of fertility islands as a promoter of the undesirable shrub invasion through positive feedback loops, Allsopp (1999) interprets the development of fertility islands of *Galenia africana* in areas of high landuse intensity in Namaqualand as a mechanism that increases rangeland productivity by resource redistribution. Schlesinger *et al.* (1996) regard increasing soil heterogeneity as a consequence of desertification and propose comparisons of soil heterogeneity, e.g. between grasslands (fine scale heterogeneity) and desert shrublands (coarse scale heterogeneity) to derive indices of desertification. Ludwig *et al.* (2005), HilleRisLambers *et al.* (2001) and Wilcox *et al.* (2003) assume the same benefits as Allsopp (1999) by formation of vegetation patterns in savannas; runoff is generated on non-vegetated sites and trapped in vegetation patches. Since water is not distributed area-wide but concentrated on small runon sites, it infiltrates deeper into the soil and is thus less exposed to evaporation. Disturbances of the sensitive relation of runon– and runoff-sites, such as clearing or overgrazing, result in resource losses and progressing degradation of the landscape. Those mechanisms are well described and analysed for banded vegetation patterns that occur in the so called tiger bush of Niger and in Australian savannas (Valentin *et al.*, 1999; Tongway & Ludwig, 2001).

Further, plants influence the weathering rate of soils, as reviewed by Kelly *et al.* (1998). Carbon dioxide that is accumulated in the soil by root respiration, and organic acids and ligands that are generated by different kinds of plant species, have a profound impact on soil pH (Drever, 1994), which in turn is being regarded as the master variable in terms of weathering processes.

3.3.2 Termites

Termites represent the most abundant invertebrate group in semi-arid and arid environments (Bignell & Eggleton, 2000). They occupy a key role in biogeochemical cycles in those landscapes and modify their environment ranging from local alterations such as infiltration rate to the creation of landscape mosaics, therefore being termed as ”ecosystem engineers” (Dangerfield *et al.*, 1998; Jouquet *et al.*, 2004a).

In general, termites are polymorphic, social insects. They live in colonies of several thousand to several million individuals (Lee & Wood, 1971), all living within the limits of a nest system, consisting of the actual nest and associated structures such as epigeal mounds, subterranean chambers, subterranean galleries, and foraging runways (Wood, 1988; Turner, 2000). Since they have a soft cuticle with poor water-retaining properties, they are susceptible to desiccation (Moore, 1969) and thus depend on the maintenance of humidity in their surroundings. Lee & Wood (1971) review different mechanisms of humidity control:

1. active transport of water
2. use of absorbent materials for construction of nests
3. metabolic water and
4. protection from excess water

Generally, termites can be grouped according to whether they are

1. living epigeal or hypogeal
2. forage primarily for wood, grass, litter or humus
3. construct distinct nests, and
4. cultivate fungi (Genus: Termitomyces) as food (Jones, 1990)

In African savannas, the fungus-growing species of the subfamily Macrotermitinae are most abundant (Eggleton, 2000). Their occurrence is strikingly obvious through their epigeal mound constructions; mounds of the species *Macrotermes michaelseni* in the Namibian thornbush savanna reach a mean of approx. 2 m in height with a maximum of 3.75 m (Turner, 2000); observations of Grohmann *et al.* (in prep.) on the BIOTA sites Omatako and Erichsfelde a bit further south resulted in means of 1.7 m with a range of 0.9 - 2.3 m. However, other Macrotermitinae species even achieve 9 m (Lee & Wood, 1971).

A description of the mound structure is given in detail in Turner (2000) and Turner (2001). In summary, it internally consists of a nest with 1.5 - 2.0 m diameter in size, which is divided into two parts: the galleries, containing the workers and reproductives, and the fungus gardens above it, consisting of an array of chambers housing fungus combs. From here, tunnels radiate below and around the nest; above the fungus garden they merge to form a central chimney that stretches upwards to the top of the mound. The chimney itself is at the center of a network of tunnels that extends throughout the mound, which is termed the "lateral connectives". They merge into vertically orientated surface conduits that are separated from the outside air by a porous covering that is 1-3 cm thick.

Mound architecture and function vary between species within the subfamily but it is agreed that they serve the purpose of thermo- and gasregulation; the metabolic rates of the colony and in particular the symbiotic fungi produce considerable amounts of heat, carbon dioxide, methane and volatile chemicals that have to be dissipated. On the other hand, the fungi gardens require a relative humidity near saturation, constant temperature of about 30°C and low concentrations of CO_2 as optimal conditions for their growth (Korb, 2003, and references therein). Thus, colonies in arid regions face the constraint between gas exchange and water loss, at times also between gas exchange and temperature maintenance (e.g. the species *Macrotermes bellicosus* in gallery forests of West Africa).

According to works of Turner (2001), respiratory exchange in mounds of *Macrotermes michaelseni* functions in a tidal way; gas exchange is triggered by metabolism-induced buoyant forces in the chimney on the one hand and a complex process of wind-induced pressure in the surface conduits on the other. However, other systems of thermoregulation have been identified such as daily circular ventilation in mounds of *Macrotermes belllicosus* (Korb, 2003).

Many studies report a strong impact of termite activity on soil properties. Mound material has been found to be enriched in Ca, Mg, Na, K (Holt & Lepage, 2000) which is probably due to an associated enrichment with clay. Further accumulations of inorganic N (Ndiaye *et al.*, 2004; Ji & Brune, 2006) and organic matter (Jouquet *et al.*, 2003, 2005; Brossard *et al.*, 2007) have been detected. However, concentrations vary between different mound materials: Jouquet *et al.* (2002a) found lower C and N contents in the galleries than in the chamber. They conclude that termites increase water holding capacity by enriching the soil with organic matter, since it is crucial to maintain moisture for the fungi-gardens. The role in N-cycling was studied in more detail by Ji & Brune (2006); they analysed the different N-species in the gut contents (NH_4^+, NO_3^-) and bodies (NH_3) of soil- feeding termites as well as in mound materials (NH_3, NH_4^+, NO_3^-) and surrounding soil (NH_4^+, NO_3^-). Their results indicated

1. an increase of ammonia and nitrate contents from parent soil towards the nest,
2. similar contents of total N in nest and parent material
3. but a participation of NH_4^+ of total N within nest material of 14% which is two orders of magnitude higher than in the surrounding soil (0.02%) and
4. NO_3^- as major source of inorganic nitrogen in the soil but NH_4^+ as dominant inorganic N-species in gut contents (20-fold than NO_3^-) and nest material (35 - 45-fold than NO_3^-)

The authors conclude from their findings that soil-feeding termites play a major role in N-cycling in humid savannas by effectively catalysing the transformation of refractory soil organic nitrogen to a plant-available form that is protected from leaching by absorption to the nest material and the adjacent soil.

Duponnois *et al.* (2005) found higher NH_4^+ contents in mound material of *Cubitermes* and *Trinervitermes* species but by contrast to Ji & Brune (2006), they also found higher NO_3^- contents in *Macrotermes* mound material. In potting experiments with *Acacia seyal* and mound material of the mentioned termite species, results revealed different effects on the stimulation of plant growth. This supports the assumption of Jouquet *et al.* (2004a), who detected different influences on patterns of some grass species by three termite species in West African Savanna, that fungus-growing termites should not be regarded as a single functional group which is commonly done. Another aspect of termites changing soil properties regards texture. It could be shown that termite mounds contain more clay than surrounding soil (Wood, 1988; Jouquet *et al.*, 2003, 2004b), that termites select particle sizes for the construction of certain nest structures (Wood, 1988; Jouquet *et al.*, 2002a), and moreover, that they collect the appropriate material from soil horizons in depths of 10 to 12 m (Wood, 1988; Holt & Lepage, 2000). Further, Jouquet *et al.* (2002b) found evidence that termites function as weathering agents on clay minerals since termite handling led to an increase in the expandable layers of the component clay minerals. The authors present the hypothesis, that termites are capable of decreasing the charge of some clay layers in a more or less irreversible way, allowing an adsorption of hydrated or polar ions between the layers. Possible explanations that have to be verified may be: a direct effect of saliva, indirect stimulation of microflora with saliva, or an incorporation of certain fungi species within their constructions. Apart from effects of termites on soil chemical parameters and texture, investigations upon changes in further soil physical properties have been conducted. Malaka (1977) found increased bulk densities on mound and pediment soil of 1.74 to 1.91 g/cm^3. Konaté *et al.* (1999) report soil water potential measured in situ in different mound depths that was significantly higher during the beginning of the dry season than in the surrounding soil and link this to texture effects. Mando *et al.* (1996) performed experiments on crusted sahelian soils by applying mulch and mixtures of wood to experimental plots which attracted termites and led, after rain simulation, to an increase in cumulative infiltration amounts, final infiltration rates, soil water content, and porosity. Other plots were treated with insecticides to keep the termites away; here, soil physical properties were not improved. Similar results were reported by Mando (1997). In their mulching experiments during three rainy seasons, an increase of water input by infiltration was achieved through termite activity. According to Léonard & Rajot (2001), infiltration increased by a factor of 2-3 due to the presence of termites in their experimental sites during three years of rainfall in Niger. At least 30 foraging holes per square meter were necessary for the effect to become significant.

The effect of the above-mentioned small scale alterations of soil through termite activity on the ecosystem and maybe even the global scale is a function of termite abundance, spatial extent of their occurrence and longevity. Darlington (1982) found a single mound of *Macrotermes michaelseni* which was associated with 6 km of subterranean galleries and 72,000 storage pits in an area of 8,000 m^2 (cited in Wood, 1988). In Nigeria, densities of 6.45 mounds per hectare were mapped by Collins (1981) of live *M. bellicosus* colonies, in addition he states the occurrence of 34.17 dead mounds per hectare. Darlington (1991) states 1 - 4 mounds per hectare in Kenya and an estimated biomass of termites of 31.4 kg dry weight per ha and in northern Namibia, Turner (2000) reports of 1.045 mounds ha^{-1}. (Grohmann *et al.*, in prep.) mapped 3.5 mounds of *M. michaelseni* per hectare including dead and live mounds. Dangerfield *et al.* (1998) states, that in African savannas standing biomass of termites is comparable with ungulate biomass. Meyer *et al.* (2003) observed the food consumption of *Macrotermes natalensis* in a South African savanna. An average of 20.2 kg ha^{-1} $year^{-1}$ were estimated. Further investigations in the context of C- and N-fluxes was conducted by Konaté *et al.* (2003) who calculated after CO_2-measurements on point and mound-scale with closed container systems an annual respiration of 27.2 g C/m^2 in total, representing 4.9% of the total aboveground net primary production in that particular ecosystem and 11.3% of the carbon not mineralised by annual fires. Gas concentrations in mounds of *C. ugandensis* in the Kakamega forest in Kenya were stated as 1,600-fold, 75-fold and 30-fold above atmospheric background for NH_3, CH_4 and CO_2, respectively, indicating striking implications for global gas fluxes. Concerning the age of live mounds statements differ widely. Collins (1981) states 15 - 20 years for *M. bellicosus* colonies in Nigeria, other authors report pottery found within termite mounds that dates back to the Iron Age when people buried them intentionally for food supply (van Schalkwyk & Moifatswane, 2000). According to Darlington & Dransfield (1987), old, abandoned nests are often recolonised. Thus, young nests may be associated with structures inappropriate to their age, which leads to errors in age estimations. Mound material is distributed by erosion, especially of abandoned termitaria. Furthermore, sheetings that are constructed for short-term foraging, might even contribute more to a distribution of termite material on parent soil (Holt & Lepage, 2000). Lobry de Bruyn & Conacher (1990) reported rates of soil translocation ranging from 0.02 - 4.7 t ha^{-1} $year^{-1}$. Lepage (1984) estimated a mass of 0.75 - 1 mm or 35 kg ha^{-1} $year^{-1}$

of eroded soil after an unusual high mortality of mounds within two years. Although some termite species occur as pests, or are regarded as such due to their competition with agricultural production (Black & Okwakol, 1997; Umeh & Ivbijaro, 1999), most authors esteem termites as agents that contribute to a continual rejuvenation of savanna soils by bioturbation and corresponding enrichment with organic matter and clay from subsoil horizons, therefore indicating a most beneficial effect on ecosystem stability (reviewed in Holt & Lepage, 2000).

3.3.3 Ants

Much like the termites, ants significantly affect the composition of soil in extant times. Dean & Milton (1993) found increased contents of phosphorus, potassium and nitrate in soils adjacent to ant nests. In nest-mounds of *M. capensis* Dean & Yeaton (1993a) determined a higher infiltrability of soil, more organic matter, phosphorus, potassium and nitrogen compared to surrounding soils and more leaf nitrogen in on-mound plants. The authors describe the soil of ant mounds as drier than intermound soils after rain, but presume a complex moisture gradient below nest-mounds similar to that in dunes where water is stored in mid-dune areas while the upper part of the dune is dry (Yeaton, 1988). This and the nutrient enrichment are regarded as an important source of patchiness in semi-arid environments that provides favourable sites for plant establishment in otherwise phosphorus and nitrogen depleted environments. This is supported by works on interactions of ant mounds and vegetation: ant nests were found to enhance seed production (Dean & Yeaton, 1993b) and plant growth; plant species associated with ant nests usually differ from species growing in adjacent areas (Dean & Milton, 1993). In temperate grasslands, they increase below-ground biomass (Dostál *et al.*, 2005). Nkem *et al.* (2000) report lower clay and higher sand and silt contents in ant-mound soils of the species *Iridomyrmex greensladei* of New South Wales as well as reduced exchangeable Ca, Mg, K and Na. Like the authors mentioned above, they found higher contents of nitrate and phosphorus on ant mound material compared to off-mound soil. Soil porosity was increased below ant nests to a depth of about 200 cm. The reduction of Na in the mounds is seen as an important ecological process avoiding sodic conditions which is also of interest concerning sustainable landuse. Further, mound soils turned out to be highly compacted within the 0-10 cm of the mound and were very stable and resistant to erosion while active, which indicates that stable biopores are maintained over a long period of time; however, when mounds are abandoned, a source for subsequent redistribution is maintained.

In coastal sand dunes, Whitford (2003) gives an account of the harvester ant *Pogonomyrmex maricopa*. This species is affected by the soil in terms of the hazard of erosion in the mobile sand dunes and responds to this environmental condition by constructing cemented caps on top of the mound. The material is derived from underlying calcium carbonate layers in the subsoil and helps the colony to survive in the unstable sands. Moreover, the partial erosion of the caps adds calcium carbonate to sand dune soil and even attracts antelopes. Lane & BassiriRad (2005) emphasise the role of ants in restoration experiments; in their study on a chronosequence of prairie soils ranging in age from 8 to 26 years post-restoration with native species, nutrient enrichment of ant mounds compared to matrix soil turned out to be a transient phenomenon; while total N, DON, NH_4^+ and total C were significantly higher for mound versus prairie soil at the 8 year old site, there was no significant difference in those parameters found on the 26-year old site. Obviously, the enrichment of ant mounds over time did not keep pace with the increase in total N of the prairie soil following 26 years of restoration.

3.3.4 Heuweltjies

A common phenomenon in winter rainfall areas of South Africa is the occurrence of earth mounds with a regular shape and a remarkably uniform pattern of distribution (Lovegrove & Siegfried, 1986). Apart from South Africa, these features are found in western North America (Arkley & Brown, 1954; Spackman & Munn, 1984; Carlson & White, 1987; Carty *et al.*, 1988), in the Peruvian altiplano (Scheffer, 1958), in Argentina (Cox & Roig, 1986), in the Kenyan highland (Cox & Gakahu, 1983; Darlington, 1985) and in Zambia (Pullan, 1979). In literature, they are referred to as hog wallows, pimple mounds, prairie mounds and mima mounds, in local South African areas they are known as "kraaltjies" or "heuweltjies" (Afrikaans: little hills).

In wide areas of the Cape Province in South Africa millions of heuweltjies strikingly characterise the landscape which is excellently visible in aerial photography (Fig. 3.1). The circular, raised earth mounds are typically about 30 m in diameter and 2-3 m in height and cover up to 25% of the landsurface where they occur. A map of its geographical distribution is provided by Lovegrove & Siegfried (1986) (Fig. 3.2). According to Ellis (2002), their occurrence is restricted to areas below the Great Escarpment; however, Petersen *et al.* (2003) found them also in the Richtersveld. They are also virtually absent on base-poor parent material such as sandstone. The mound density ranges from 281 - 498 mounds/ km^2 from Lambert's Bay to Outdtshoorn (Lovegrove & Siegfried, 1986), evidently following a biomass and rainfall gradient (Lovegrove & Siegfried, 1989).

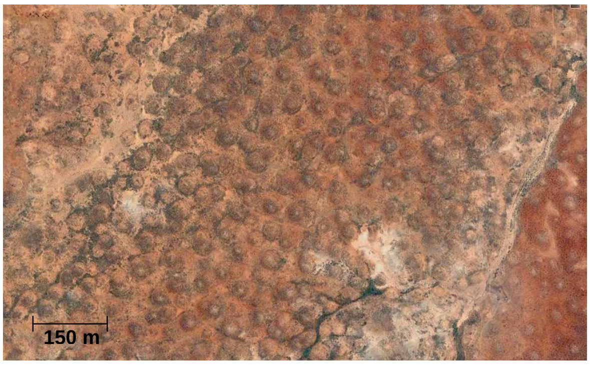

Fig. 3.1: Aerial photography of heuweltjie-pattern in the landscape near Soebatsfontein (Source: Google Earth).

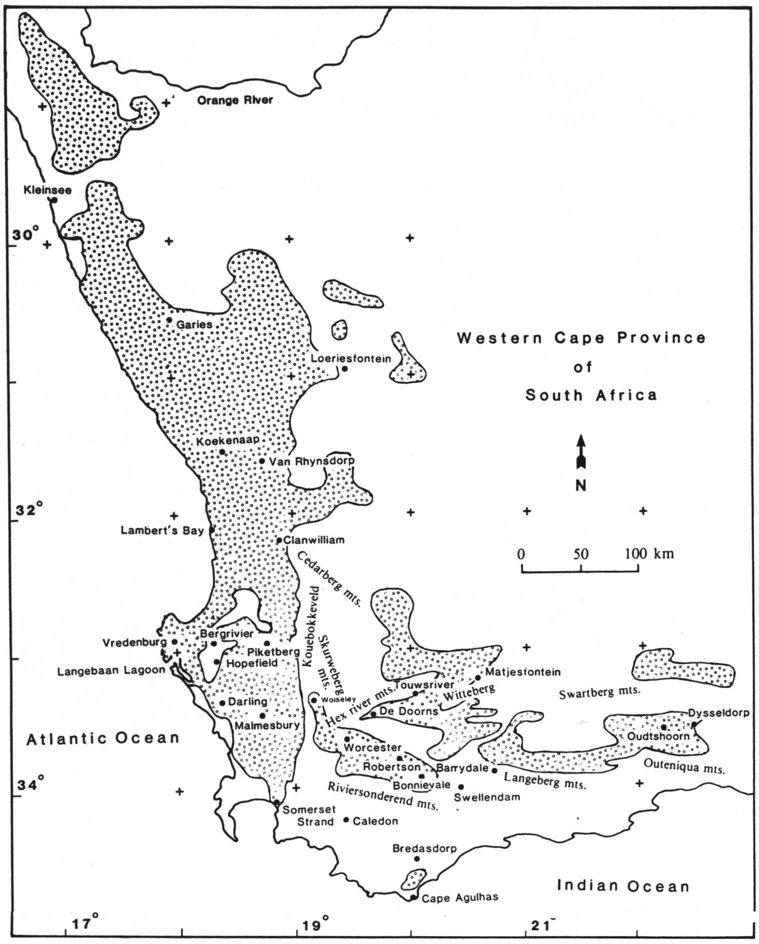

Fig. 3.2: Distribution of heuweltjies in Southern Africa (Source: Lovegrove & Siegfried (1986)).

For a long time heuweltjies only received scant attention from researchers; although this phenomenon was known, the genesis was subject to much speculation and literature was mostly found in form of anecdotal accounts instead of proper scientific studies (Lovegrove & Siegfried, 1986). Hoyer (2004) presumes that this might have been due to the fact that during the apartheid regime, research activities focused mainly on fertile soils in more eastward areas of South Africa whilst in the western coastal zone interest was rather placed on geological surveys for prospecting and exploitating of mineral resources.

However, the discussion on heuweltjies arose again during the 1990s encompassing varying disciplinary aspects such as their formation, their role for soils, vegetation and ecology as a whole. Especially the question of genesis was paid some attention and was discussed controversially. Early hypotheses on heuweltjie formation are reviewed by Lovegrove & Siegfried (1989):

- Limestone–Faulting–Hypthesis (van der Merwe, 1940); the underlying fact leading to this hypothesis is the occurrence of a semi-concreted layer of limestone, approx. 0.3 m thick, that is continuous below the earth mounds and discontinuous in intermound soils. The author assumes that past faulting or folding of the sedimentary shales led to the formation of those layers and to ”irregular projections and lumps of limestone in the surface shale horizon”, eventually forming the earth mounds.

- Dorbank–Erosion–Hypothesis (Slabber, 1945); this hypothesis is also based on the occurrence of a limestone-rich dorbank that covered these areas during a past semi-arid climatic period. This period was followed by a wetter period during which erosion of the dorbank took place. Some circular patches were protected from erosion by associated plant communities and later became earth mounds

- Termite–Tree–Hypothesis (van der Merwe, 1940): a second hypothesis of van der Merwe (1940) aims at the explanation of mound formation in higher rainfall areas by the combined influence of ants/ termites and trees. *Olea europea africana*-trees were dominant in those areas and led to the accumulation of sediments and organic material by wind trapping of dust, recycling of leaves, and faeces by animals that were attracted by the trees. The materials were incorporated into the soil by ant and termite based bioturbation

- Wind–Action–Hypothesis (Ten Cate, 1966); investigations on earth mounds in the Overhex-Nuy area could neither detect signs of termite activity nor limestone layers. Since the only characteristic feature of the mounds is a thin layer of fine material, the author concludes that wind and water action are the only agents that could account for the formation

- Termite–Climate–Hypothesis (Burgers, 1975); in this hypothesis, termites step into the focus for mound origination. During different climatic regimes some 12,000 years ago, the areas were covered by grassland and favoured the appearance of termites such as *Macrotermes spp.* They constructed termitaria up to 10 m in height and 30 m in diameter. However, with changing climatic conditions, the mounds were evacuated and steadily collapsed to lower and wider mounds. Their complete disappearance by erosion was prevented by a succession of associated plant communities. Subsequently, the mounds were colonized by other termites, such as *Hodotermes viator*, which probably account for the recent morphology of the heuweltjies

The latter theory is also underpinned by Pullan (1979) who states that moribund termite hills are frequently found that are not subjected to erosion due to a dense vegetation cover.

Lovegrove & Siegfried (1986) and Lovegrove & Siegfried (1989) reject former hypotheses and suggest the Termite–Mole-Rat–Hypothesis. According to this work, termites of the genus *Microhodotermes viator* usually form sub-terranean hives in approx.

0.5 m depth. In shallow soils, however, they construct small conical mounds above the hives. The mole rat *Cryptomys hottentotus* builds subterranean nest chambers and food caves, which are endangered by flooding in the shallow soils in the Western Cape's wet winters. Therefore, *C. hottentotus* colonises the termite mounds. During the dry conditions in spring and summer, soil builds up around the termite mounds as a result of renewed burrowing activities of the mole rats. Hence the formation of the mounds and their pattern of spacing are a consequence of intra-specific competition and lateral soil translocations of the mole rat. This hypothesis is supported by findings of Arkley & Brown (1954) and Nelson (1997) on the formation of Mima mounds that has been linked to the burrowing activities of geomyid pocket gophers. In addition, the authors bring forward the argument of the accordance of the geographical distribution of heuweltjies, *C. hottentotus* and *M. viator* in South Africa and the fact that most earth mounds that were examined are inhabited by *M. viator*. Cox *et al.* (1987) tested the Termite–Mole-Rat–Hypothesis by analysing the small-stone content in heuweltjies occurring on a range of clay soils to coastal sands in Robertson and Clanwilliam. Since non-concretionary stones larger than 50 mm are rare in mound soils, but abundant in the soil of intermound areas, the findings support the idea that mole rats have substantially contributed to mound development. So have termites, because otherwise there would have been a greater concentration of small stones in mound rather than in intermound soils due to subsequent erosion of fine material from the mounds into the intermound areas.

In contrast to the Termite–Mole-Rat–Hypothesis, Moore & Picker (1991) assume the formation of heuweltjies to be only termite-driven, with mole rat activity as a recent side-effect and leading to disturbance rather than accumulation of mound material. Their hypothesis refers to examinations of exhumed mounds at the edge of a dam in the Clanwilliam district. In none of the numerous heuweltjies they found fossil structures attributable to mole rats; however, they found relic and recent evidence of termite activity. They also described the calcretisation of the basal parts of the earth mounds and refer that to groundwater interaction with the more alkaline mound soil. This effect forces the termites to move upwards, which explains the growing of mounds. Midgley & Hoffman (1991) describe this as an "onion skin effect".

Later, Ellis (2002) relates the occurrence of hardpans[2] within the heuweltjies and in parts between them directly to the influence of termites. During thousands of years, termites accumulated biogenic material which led to a build-up of bases and silica. Their activity also resulted in the creation of a fairly well-drained material with a high soil pH compared to interheuweltjie soils. In regions of low rainfall, termite activity ceased with climatic changes. $CaCO_3$ was leached to a shallow depth to form a petrocalcic horizon at the centre of the mound. Also, due to the high pH values at the center parts silica

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[2] silicic or calcareous solid banks; according to WRB termed as petrocalcic horizon when cemented by calcium carbonate, petroduric if cemented mainly by secondary silica; the qualifier hypercalcic is used when soft carbonates accumulate in a way that most of the pedological structures disappear and continuous concentrations of calcium carbonate prevail. A hypocalcic horizon is defined by having a calcic horizon with a calcium carbonate equivalent content in the fine earth fraction of less than 25 percent and starting within 100 cm of the soil surface

species were mobilised during rain events and translocated vertically and horizontally to the periphery of the mound, where they precipitated again, thus creating a petroduric horizon at the heuweltjie margins. Once a petroduric horizon had formed, infiltration capacities at the margins decreased and runoff was generated during rain events. Water was thus accumulating at the heuweltjie edges, where it infiltrated again. In this zone, water-soluble silica and soil pH appeared to be at their highest, so that silica was further mobilised and precipitated further on the bottom side of the petroduric horizon (Fig. 3.3).

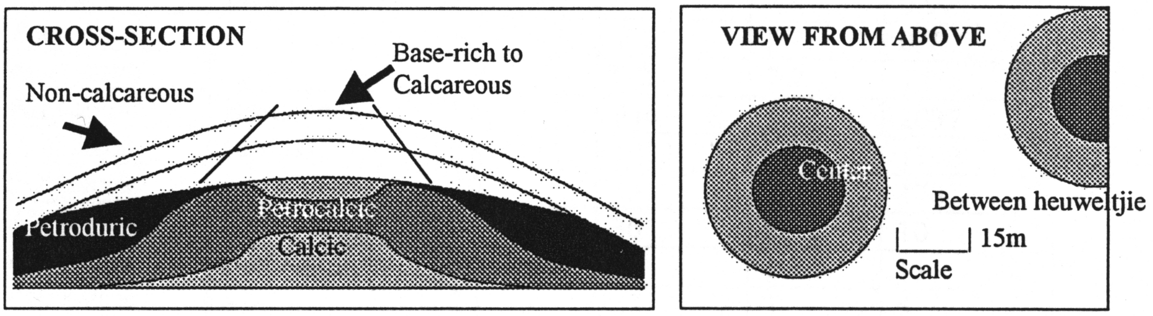

Fig. 3.3: Scheme of heuweltjie composition in terms of horizons/ materials (Source: Ellis (2002)).

Ellis (2002) further addresses the issue of different heuweltjie types and varying degrees of termite activity on a rainfall gradient. Where rainfall is low (<250 mm/a), termite activity is relic and mounds are characterised by calcretes and duripans in mounds and also in surrounding inter-mound areas. In higher rainfall zones (250 - 450 mm/a), termite activity exists but is limited to the centre of most mounds, on the oldest mounds activity has ceased. Here, mounds contain calcretes and duripans; however, they are not found off-mounds. With increasing rainfall (>450 mm/a), no termites are found; a broken hardpan and base-rich soil material is found on the mound. Inter-heuweltjie soils have moderate to low base status without any of the above-mentioned hardpans.

The findings of Ellis (2002) that postulate mound formation over thousands of years are in line with observations on mound age. Coaton (1981) conducted a radiocarbon dating of two fossilised nests found during construction work near Clanwilliam. The nests turned out to be approx. 30,000 years old but were not clearly associated with heuweltjies. Another estimation of age was conducted by Moore & Picker (1991). A ^{14}C dating of calcretes of heuweltjies in the dam of Clanwilliam revealed an age of 4,000 years. A very recent work on heuweltjie age is a publication of Midgley *et al.* (2002). Heuweltjies of Clanwilliam and Elandsbay were established before the last glacial maximum 20,000 years BP. They even go a step further by stating that during this time, climate was cooler and wetter, which accounts for the assumption, that not the recent termite genus *M. viator* was the originator of the heuweltjies but another genus that remains unknown. Hence, the authors regard the heuweltjies as fossil features from the late Pleistocene.

Another approach to explain the heuweltjie phenomenon is presented by Laurie (2002). He focuses on the overdispersion of the features and shows that this pattern of a hexagonal array is the only stable equilibrium assuming optimal transport of resources to central places. The regular pattern in a heuweltjie-landscape is in his opinion the result of termites' several thousand years of movement towards this equilibrium .

Interestingly, most recent investigations diverge again from regarding heuweltjies as relic features; Picker *et al.* (2007) found evidence for a positive relationship between rainfall and mound density in areas with < 350 mm/a and conclude that mounds originate from recent activity of *M. viator*. The fossilised nests found below heuweltjie mounds are referred to the sister taxon *Hodotermes mossambicus*, which is associated with grassland and restricted to the summer rainfall parts of South Africa, or to times with different climatic conditions, respectively.

Further works regarding heuweltjies refer to their ecological role. According to Midgley & Musil (1990) and Petersen *et al.* (2003), heuweltjie soils are enriched in Ca, Mg, K, P, Mn and N compared to intermound soils. This finding again supports the influence of termite activity in mound formation, since the same nutrient enrichment is reported from different kinds of termite mounds (Lee & Wood, 1971). Further, mounds have increases pH-values and silt contents, and they favour different plant communities; on-mound either deciduous and evergreen plant growth forms are found while off-mound only evergreen forms occur. This finding can be explained by the higher demand of deciduous plants on nutrient availability due to the more rapid leaf turnover rate compared to evergreen plants (Midgley & Musil, 1990). Additionally, they are interesting spots for animal activity, be it for the construction of nests or lairs or the use as midden sites for animals that bury their dung such as felids, aardvark and steenbok. Thus, heuweltjies increase habitat diversity and, as a result, biological diversity (Milton & Dean, 1990).

3.3.5 Fairy Rings

A further feature similar to heuweltjies but still rather mysterious in origin occurs in Namibia. The so-called "fairy rings" or "fairy circles" are regular patches in the landscape that are characterised by bare, slightly concave depressions surrounded by a fringe of tall grasses, in most cases of the species *Stipagrostis giessii*. They are embedded in a matrix of vegetated soil, dominated by *Stipagrostis uniplumis* grasses (Becker & Getzin, 2000). The fairy rings occur in a broken belt of the pro-Namib following 50 and 10 mm isohyet line (van Rooyen *et al.*, 2004). Their diameters range between 2 and 12 m (Moll, 1994), with decreasing size from north to south. Also, in the southern part of the distribution range, the fringe is not as well developed or even absent (van Rooyen *et al.*, 2004). Some observations have been undertaken regarding the density within the landscape; Moll (1994) reports 36 to 47 rings per hectare at Giribes, which approx. matches the results of Albrecht *et al.* (2001) who state 3,484 patches/km^2 on farm Wolwedans, located in the Namib Rand Nature Reserve. Microbiological investigations of Eicker *et al.* (1982) showed similar trends compared to vegetation; aerobic microbial populations exhibited a density which paralleled that of the higher plants of these soils. The origin of the fairy rings remains a mystery to this day. Apart from some anecdotal suggestions such as electromagnetic waves, land mines or rolling spots for zebras and oryx, main hypothesis involved

1. the influence of allelopathic substances through formerly existing individuals of the plant species *Euphorbia damarana* and
2. the involvement of harvester termites

The former is proposed by Theron (1979) and indeed potting experiments revealed inhibited growth of plants in soil from the barren parts of the fairy ring, while plants developed quite well on edge soil (van Rooyen *et al.*, 2004). In similar experiments conducted by Albrecht *et al.* (2001), seedlings established on both soils, as long as sufficient water was available; however after drying and rewetting cycles, seedlings in bare soil died. This phenomenon is referred to inhibited growth of side roots (Albrecht *et al.*, 2001), which explains also the observance that sometimes seedlings establish under natural conditions in fairy rings as well after good rain events but invariably die after drying. However, this hypothesis could be rejected by van Rooyen *et al.* (2004) by their reports on long-term monitoring of fairy rings in the Giribes Plain where *E. damarana* grows in the matrix between barren patches. Within 22 years, fairy rings as well as individuals of *E. damarana* could be relocated; none of the patches had disappeared. No signs of new barren patches formed at dead *E. damarana* positions could be identified. Termites are seen by Moll (1994) and Becker & Getzin (2000) as the most likely agent in the formation of fairy rings. Moll (1994) based this on the occurrence of termite casts within the ring. On the other hand, those casts were missing in the matrix. However, according to his hypothesis of a construction by *H. mossambicus* colonies during wet cycles, a die-back during dry periods and a subsequent colonisation by other species, the author himself concludes that the fairy rings should be a dynamic pattern, which is not so, according to van Rooyen *et al.* (2004) as outlined above. The approach of Becker & Getzin (2000) was criticised by Grube (2002) since the behaviour of *H. mossambicus* was not taken adequately into account. Van Rooyen et al (2004) points out that a foraging by termites hypothesis would result in patches with grass stubbles instead of completely depleted sites since no termite species eat the entire plant. What supports the idea of a termite contribution is the fact that similar R-values of distribution were calculated for both, fairy circles and heuweltjies. This again matches with the overdispersion discussion of Laurie (2002), as cited above.

3.3.6 Mammals

Small mammals such as mice, mole rats, squirrels and suricates are common inhabitants of Southern African habitats. Further, antelopes, warthogs, aardvarks, porcupines and some small predators (foxes, jackals, felines) are the most abundant larger mammals in the areas investigated in this work. They all exhibit an impact on soils either directly, or indirectly by plant consumption.

The main direct influence of mammals on soils is performed by their burrowing activities that lead to intensive bioturbation. As a compilation of data of several researchers in the review article of Whitford & Kay (1999) reveals, up to 15 - 20% of the surface in semi-arid areas with high forage activity of mammals may be covered by ejected material from foraging digs, caches, and temporary shelter burrows. Alone nest mounds of dune mole rat (*Bathyergus suillus*), hottentot mole rat (*Cryptomys hottentotus*), cape mole rat (*Georhynchus capensis*), and naked mole rat (*Heterocephalus glaber*) combined covered 28,2% of a study area in the Cape Province (Reichman & Jarvis, 1989). Digging activities of burrowing animals including small mammals lead to upward translocation of soil forming rock and with that to a transport of various chemical substances into the active soil layer (Abaturov, 1972). Therefore, they act as a nutrient pump in arid environments. A further effect of bioturbation is the increase of porosity and decrease of bulk density, respectively (Kerley *et al.*, 2004), which results in increased water infiltration and evaporation (Whitford & Kay, 1999). Further impact is reported for organic matter concentrations and microbial activity. Ayarbe & Kieft (2000) report of the influence of banner-tailed kangaroo rats (*Dipodomys spectabilis*) on these parameters in the Chihuahuan Desert shrubland. In mound soils, respiration, TOC, and C_{mic} were enhanced compared to surrounding soils. Feces and urine influence soil chemical composition (Sieg, 1988) and contribute to the development of fertility islands (see 3.3.1). Higher surface roughness through mammalian disturbances of soils might on the other hand result in increased erosion rates (Whitford & Kay, 1999). Rhizomymid mole rats (*Tachyoryctes splendens*) in Kenya (Cox & Gakahu, 1987), pocket gophers in the Western USA (Arkley & Brown, 1954) or mole rats (*Cryptomys hottentotus*) in South Africa (Cox *et al.*, 1987) are thought to be the main or minor agent of mima and mima-like mound formations (for instance heuweltjies; see Chapter 3.3.4), therefore contributing to topographical variability of habitats and consequently soil- and biodiversity.

Indirectly, small mammals may affect soil properties as a result of altering plant distribution and thus patchiness of soil properties such as organic matter and nitrogen availability. Seed caching has been reported to either resulting in increased germination and survival or to a reduction of seed availability and biomass production by consumption or accumulation (Sieg, 1988; Longland *et al.*, 2001). Small herbivores might play an important role in preventing woody plant encroachment as suggested by Weltzin *et al.* (1997). The authors found evidence that prairie dogs and associated vertebrates were primary agents of pod removal of *Prosopis glandulosa* (honey mesquite) that became abundant after their eradication. Similar results were obtained by Gutiérrez *et al.* (1997) who tested the effect of predator and herbivore (*Octodon degus*) exclusion on vegetation structure on a semi-arid Chilean site. The experimental exclusion of the herbivore led to an increased cover of some shrubs and a perennial grass and a decreased cover and seed densities of several ephemerals. The effects of the exclusion of the predator, however, were less clear.

From a soil-chemical perspective, the effect of large mammals such as ungulates on soils is the maintenance of resource heterogeneity esp. concerning N and P. Augustine *et al.* (2003) observed the effect of grazers on N and P distribution in a Kenyan savanna ecosystem. Here, heterogeneity of soil exist due to a traditional pastoral management system where herders pen their cattle over night in so-called *bomas*, brush-ringed corrals. Abandoned boma sites still exist as glades in the bushland and are nutrient enriched through former urine and faeces accumulation. They form sites with a unique vegetation composition and high forage quality and therefore attract antelopes as well as commercial livestock. Hence, the concentration of N and P because of excrements is continued. Augustine & McNaughton (2006) go one step further by linking rainfall patterns, aboveground net primary productivity (ANPP) and N-cycling to grazing. In a high rainfall year, ANPP was increased by grazers on nutrient-rich glades and suppressed on nutrient poor bushland site. The underlying cause is the provision of plant available N at the onset of the growing season in the glades and simultaneously a reduction of N-mineralisation in the growing season. This resulted in a net increase in N-availability at glade sites and a net decrease in N-availability at bushland sites.

On the other hand, Sankaran & Augustine (2004) investigated relations of herbivores and decomposers in a Kenyan savanna. Within only two years of grazer exclusion in an exclosure experiment, microbial biomass C increased by 25 - 47% and microbial N by 20 - 37% in soil of fenced grassland across all levels of soil fertility. The reason for the negative relationship between grazers and decomposers is a result of the reduction of plant carbon input on soils that even without grazing just suffices to meet maintenance requirements of microbial populations.

On the soil-physical side, alterations by ungulates occur due to trampling. This may be beneficial in terms of seedbed preparation for some species (Winkel & Roundy, 1991) or negative because of soil compaction and bare patch development (Stephenson & Veigel, 1987) or destruction of soil crusts and resulting vulnerability to wind erosion (Belnap *et al.*, 2007). Since larger animals cause stronger trampling effects than smaller species (Cumming & Cumming, 2003; Thompson Hobbs & Searle, 2005), this issue has a strong impact with regard to cattle and other human-induced larger mammals.

3.3.7 Biological Soil Crusts

Apart from higher plant species, mammals and insects, further organisms exhibit a significant influence on dryland soils that might be underestimated when first spotted. So-called biological soil crusts (BSC) are a common phenomenon in arid and semi-arid environments. They consist of varying proportions of biota such as cyanobacteria, algae, microfungi, lichens and bryophytes, accounting for the biological component of the BSC. These organisms are living within and on top of the uppermost millimeters of the soil, forming with this abiotic component a coherent, crusty surface layer that ranges in its properties from tough to soft, from light to very dark colours and from a rather smooth to a quite rough surface (Belnap *et al.*, 2001a).

Büdel (2005) distinguishes between two general forms of BSC, the pioneer crust and the climax crust. The pioneer crusts form after disturbances and act as an initial succession phase; in semi-arid regions they are mainly composed of cyanobacteria and occur commonly. The climax crusts, however, are of permanent character, more complex in their biotic compositions and more restricted to harsh environments such as hot and cold deserts, where the conditions for vascular plant growth are insufficient and competitors for light are therefore missing.

Biological soil crusts exert influence on ecosystems in terms of

- hydrology
- erosion processes
- and nutrient cycling

The interrelation between BSC and the soil moisture regime is discussed in chapter 3.4. Their role in erosion processes is evaluated in different ways depending on the kind of erosion (water or wind erosion), the geographical setting and the soil properties. In the Chinese Gurbantunggut Desert, findings of Zhang *et al.* (2006) indicate that microbiotic crusts function as soil-stabilising agents, protecting the soil surface from wind erosion. Algean filaments pervading the top centimeters of the soil, and exopolysaccharides, exuded by the biota, not only conglutinate fine particles with each other but also bind and entrap sand grains. Moreover, disturbances of the surface resulted in decreased soil resistance to wind erosion, as the authors could show in wind tunnel tests with varying wind velocities and degrees of disturbance. Experiments with portable wind tunnels conducted by Belnap & Gillette (1998) in the Chihuahuan Desert led to similar results: threshold friction velocities of undisturbed crusts were well above wind forces occurring at the study sites.

Concerning water erosion, the beneficial role of the BSC is less clear as reviewed by Belnap *et al.* (2001b) and Belnap (2006) (see also chapter 3.4); in Australia, however, landscapes with a BSC-cover are generally regarded as more productive and stable in terms of erosion (Eldridge, 2001).

Another important aspect of BSC in ecosystems is their role in nutrient supply. Since arid landscapes are known as nitrogen deficient environments, and nitrogen is the macro nutrient limiting plant growth, the N-fixation ability of some BSC bears utmost significance. This property is attributed to cyanobacteria and cyanolichens that possess heterocysts, thick-walled cells in which N-fixation takes place (Paerl, 1988). In some non-heterocysteous soil genera such as *Microcoleus*, N-fixation has also been detected but according to works of Steppe *et al.* (1996), this is linked to associated bacteria.

N-fixation depends on water availability and temperature; estimations of N input found in literature ranged from 1.4 to 9 kg/ ha^{-1} $year^{-1}$ on different crust types in Utah (Belnap, 2002). However, a study conducted in Southern Africa by Aranibar *et al.* (2003), led to estimations of 8 to 44 g N/ ha^{-1} $year^{-1}$ in BSC. As the authors point out themselves, these results are orders of magnitude lower than in other studies. They refer this to the exeptionally wet conditions during the year in which the investigations were carried out: wetting and rewetting led to an increased availability of soil mineral N that inhibits nitrogenase synthesis and therefore causes a decreased N-fixation rate. This example shows the high variability of N-fixation rates depending on crust type, cover and environmental conditions.

Further, BSC contribute to carbon fixation. Crust production and thus C-input by BSC are reported to range between 0.4 - 2.3 g C/ m^{-1} $year^{-1}$ (cyanobacterially dominated crusts) and 12 - 37 g C/ m^{-1} $year^{-1}$ (crusts where lichens and/ or mosses on top of the soil surface contribute to biomass production) (Evans & Lange, 2001). Büdel (2002) suspects that this might have implications for the global CO_2 budget, since most ecosystem balances do not take biological crusts into consideration (Büdel, 2002).

Papers of Garcia-Pichel & Belnap (2001); Büdel (1999); Garcia-Pichel & Belnap (1996) indicate that the photosynthetic activity of biological soil crusts and lithogenic crusts may increase pH of the surrounding medium up to 3 pH-units; since pH is linked to the availability of nutrients in soils, this has considerable implications within the ecosystem. Moreover, Harper & Belnap (2001) and Harper & Pendleton (1993) could show that BSC alter the uptake of bio-essential minerals by associated vascular plants. In greenhouse and field experiments cyanobacteria and cyanolichens such as *Collema* increased levels of N, Cu, K, Mg and Zn in plant tissues while uptake of Fe and P correlated negatively with the presence of BSC. In soils, availability of N, K, P, Ca, Mg and Mn were increased in crusted soil compared to non-crusted sites. However, these authors do not link this phenomenon explicitely to the modification of pH values, although this seems likely in terms of the limited uptake of Fe in plants; however, they explain the reduction of Fe and P with competition between the soil crust organisms and the roots of seed plants. The observations upon the increased uptake of other elements are refered to the nature of different secretions of the biota within a BSC: microbial exopolymers act as polyanions that prevent excess quantities of highly charged molecules such as heavy metals from approaching the cell surface, while concentrating growth-promoting nutrients present at low concentrations in the surrounding environment. Metal chelators such as siderochromes maintain metals that would otherwise be precipitated in solution (Belnap *et al.*, 2001c).

3.4 Small Scale Soil Patchiness Affecting Hydrology

Rainfall in arid and semi-arid areas (also referred to as deserts and semi-deserts) is scarce, and water availability in addition limited by high potential evaporation rates. Therefore, the definition of semi-arid and arid environments is defined today by both, mean annual precipitation (MAP) and evaporation, and their relation to each other, respectively. According to Lexikon der Geowissenschaften. Band 1 (2000), arid regions are defined by evaporation rates permanently exceeding rainfall, while semi-arid regions are characterised by temporary aridity of more than six months and an annual rainfall between 250 and 500 mm/year. However, earlier definitions focus on annual precipitation with extreme arid regions receiving less than 60-100 mm MAP, arid regions ranging from 60-100 mm to 150-250 mm and semi-arid regions matching 150-250 to 250-500 mm MAP (Noy-Meir, 1973).

Apart from precipitation and evaporation rates, further conditions connected with the quality of water supply control plant growth and biodiversity in drylands, mainly the distribution of yearly rain events, their seasonality, erosivity and predictability. Along the BIOTA transect, a rainfall gradient exists with high mean annual precipitation of 400 - 600 mm in the Cape region, decreasing gradually to a minimum of 50 mm at the border to Namibia and then increasing again to 600 mm in Rundu, near the border to Angola. Two rainfall regimes occur along this transect; in South Africa, winter rainfall is dominant, with rain events occuring in the winter months between July and September. The rains appear typically as light drizzle events, exhibiting - if at all - weak erosivity effects. They are also highly predictable and cover wide areas. Since rainfalls occur during winter when temperatures and corresponding evaporation rates are low, the water supply is utilised more effectively by the vegetation. In Namibia, however, summer rainfall prevails. These rain events are less predictive, occur often only locally as heavy rains and thunderstorms that favour the generation of runoff and erosion. At the transition zone between the rain regimes, comprising the Richtersveld area and the Oranje valley, annual precipitation is not only extremely low but also composed of both winter- and summer rains. Occasionally, these overlaps extend even to the Namaqualand and the Nama Karoo.

In drylands, manifold physical adaptions and life strategies are found that developed in response to the harsh, dry conditions. Species adapted by evolving deep root systems (*Acacia mellifera*, *Welwitschia mirabilis*), by the ability to dig deep to reach groundwater (termites), by storage systems or organs (leaf and stem succulents) or by dormance (annual species) to name but a few. Beyond the survival strategies of species, life in extreme surroundings is possible by highly complex and sensitive interactive processes between biota and abiotic components maintaining small habitats as well as perpetuating the functionality of whole ecosystems and even landscapes. The key to these eco-functions lies within the development of patches on varying scales.

The first step in the hydrological cycle is the entry of rain into the soil. This step is controlled by an infiltration capacity which in turn is limited by a patchy distribution of species and soil crusts. Two crust types have to be distinguished: physical or mineral soil crusts (MSC) and biological soil crusts (BSC), as earlier referred to in Chapter 3.3.7.

Several recent publications deal with the formation and ecological significance of MSC. Francis *et al.* (2007) summarize findings on the complex processes behind physical crusting. The main agent in formation is the impact of raindrops on bare soil, the dispersion of fine particles (clay and silt), the entry into the soils and the downward movement of the suspension and, consequently, the crust formation due to an increasing coherence when the soil dries. Based on relationships between infiltration data derived by laboratory experiments according to Mills & Fey (2004a) and on data on hundreds of surface soils sampled across the BIOTA transect, soil properties most strongly increasing crusting tendency were identified as water-dispersible silt and water-dispersible clay, followed by chemical properties such as EC, sodium status, organic C content and certain clay minerals such as mica (Mills *et al.*, 2006). This corresponds to the findings of Mills & Fey (2004b) and Mills & Fey (2004c) who investigated factors controlling the tendency to crust in soils; these factors are vegetation (crusting tendency is higher on exposed soils compared to soils under vegetation due to lower soluble salts and labil carbon contents and an associated increase in the dispersion of clay), geology (crusting tendency was increased on soils derived from shale compared to soils with dolerites as parent rocks), cultivation (in upland grassland, cultivation of maize and rye enhanced crusting) and fire (crusting was greater in burned plots due to reduction of soil C and soluble salts as welle as greater contents of exchangeable sodium percentage).

While MSC are generally seen as indicators of degradation reducing infiltration and leading to runoff and erosion, the impact of BSC on degradation processes is less clear. Authors, favouring the opinion that BSC might rather benefit an ecosystem with regard to erosion, argue with a general coverage and reduction of raindrop impact (Eldridge & Greene, 1994), a stabilisation of unconsolidated soils such as desert dunes (Zhang *et al.*, 2006) and the formation of aggregates due to the input of organic matter to the soil (Belnap, 2006), which leads to increased infiltration rates, less runoff and less erodibility. Other findings indicate the contrary: according to laboratory and field examinations by Kidron *et al.* (1999), exopolysaccharid sheaths and filament growth of algae and filamentous cyanobacteria lead to pore clogging and hence reduced infiltration rates. Furthermore, in initial stages of rainfall, water-repellent properties (hydrophobicity) of the dried BSC-surface may produce an initial peak of runoff.

Warren (2001b) concludes from various publications that the effect of BSC to water erosion depends strongly on the kind of taxonomic and successional groups; moss and lichen crusts tend to increase infiltration while smooth soil crusts composed mainly of cyanobacteria rather hamper water entry into soil (Warren, 2001a). This is especially obvious in sandy soils, where infiltration is originally high, but lowered by crusting (Eldridge *et al.*, 2000). Here, it was suggested that this non-uniform distribution and concentration of water might even be crucial for plant growth.

A synopsis of the different and by times contrary findings is given by Warren (2001b) who concludes that clay-percentage might be the determining factor that controls the infiltration rate by the combined aggregating effects of organic matter, provided by the biota, and clay. He suggests a threshold of 15% clay above which aggregates form and enhance infiltration. However, where combined silt and clay content of the soil exceed 20%, and the ratio of silt to clay is at least 2:1, the presence of vesicular structures restricts infiltration. This conclusion may in parts be valid for both, BSC and MSC. The vesicular horizons described by Miller (1971) are also referred to as "foam soils" by Volk & Geyger (1970) who also observed a reduced infiltrability where these features appeared.

A non-uniform distribution of water is regarded as crucial for plant growth in resource limited environments (Eldridge *et al.*, 2000; Allsopp, 1999; Ludwig & Marsden, 1995). Water that impinges on a bare, crusted surface in a desert, will accumulate as a thin layer on the soil surface and then run off following a topographical gradient. Eventually, it will reach a slight depression, a cracky soil surface due to increased clay or stone content, or a shrub with increased infiltration rates below its canopy. Here, the water will percolate. Since this accumulated water may infiltrate deeper into the soil than it would have with a uniform distribution over the whole area, it is less prone to evaporation and thus its storage more effective.

Needless to say, patchiness in terms of soil texture, as for example exhibited in areas with heuweltjie-occurrence (see chapter 3.3.4) do also have an effect on hydrology and consequently plant growth; however, the underlying principles of hydrological importance differ widely compared to humid areas and should be considered here. Sandy soils in humid areas are considered as less valuable in terms of water storage when regarding the available estimates and measures of water holding capacity for texture classes. The opposite is valid in arid and semi-arid areas as described in detail by Petersen (2008): sandy soils in drylands have got properties that proof advantageous in these ecosystems: first, they have higher infiltration rates compared to loamy textures, and second, the water holding capacity of fine and medium sand is only little less compared to loamy sand. The importance of high infiltration rates lies within the above described concentration of runoff water in deeper soil layers. This is of crucial importance since the rates of potential evaporation in arid and semi-arid landscapes are high, for instance, Mendelsohn *et al.* (2002) states 1800 - 3500 mm/ year for southern Namibia. The evaporation of water takes place in upper soil layers, hence, textures with high sand contents and the corresponding low capillary rises of soil water from deeper layers are more suitable and provide a better protection of this resource. This is called the *inverse texture effect* and is another diagnostic criteria for semi-arid and arid environments (Noy-Meir, 1973; Sala *et al.*, 1988). As stated by Petersen (2008), the inverse texture effect is valid for all arid and semi-arid sites along the BIOTA-transect and is therefore an important aspect for the understanding of vegetation patterns in these ecosystems.

3.5 The History and Status of Soil Degradation in Southern Africa

There are several forms of degradation endangering the sustainable use of Southern African soils. Amongst them are salinization, waterlogging, acidification, soil mining, soil compaction and soil pollution, but most severe and mainly taken into account in this work is the degradation by water erosion and crusting.

The World Map on the Status of Soil Degradation (Oldemann *et al.*, 1991) shows that water erosion affects up to 60% of South Africa's surface area. For Namibia, the data seems less severe with a 21-% degraded area (see Fig. 3.4). However, Klintenberg & Seely (2004) generated a land degradation risk map for Namibia based on indicators such as population, livestock, rainfall and erosion that reveales that far more than 20% of the land surface is endangered.

The state and history of soil degradation in South Africa is thoroughly reviewed by Garland *et al.* (1999). According to these authors, estimations on soil loss by water erosion are mainly derived from mean annual sediment yield data and might therefore hold larger errors. Nonetheless, using the data acquired in this manner leads to a loss of soil due to water erosion in absolute numbers of 0.8 to 4.0 tonnes per hectare per year. Compared to the 7.15 t ha^{-1} $year^{-1}$ estimated for Africa as a whole, or 2.7 t ha^{-1} $year^{-1}$ for Australia, the perspectives seem less dismal as expected from popular perceptions. However, since soil formation rates are thought to be about 30 times slower than rates of soil loss, these approximations are far from optimistic.

Another aspect of soil erosion especially in Southern Africa is the fact that its dimensions and economic consequences are not equally distributed; some regions are indeed severely affected by soil loss in terms of sheet, rill and gully erosion. In many cases, the patterns between severely and light degraded areas reflect the spatial extent of historical communal lands with their open access grazing systems and commercial areas. Socio-economic constraints are considered as one of two main causes for degradation in Southern Africa, owing its origin to colonial and apartheid legislation as reviewed by Turner & Ntshona (1999):

In 1913 the Union of South Africa, established in 1910 as a British dominion under white minority rule, enacted the *Native Land Act* in which less than 10% of the land was set aside for native reserves ("homelands" or "Bantustans") whilst black people were prohibited to purchase land outside these homelands. Thus, black people were only allowed to live outside the reserves when they could prove that they were under white employment. During the same time, the South African governement became aware of soil erosion and made it a major concern. Solution to the problem was sought in scientific (European) land use practices whereas native land tenure practices where regarded as unscientific and environmentally destructive (Dodson, 2004).

While racial land allocation was the ignition of intensifying degradation processes in the homelands, the effect was further aggravated by following governmental enact-

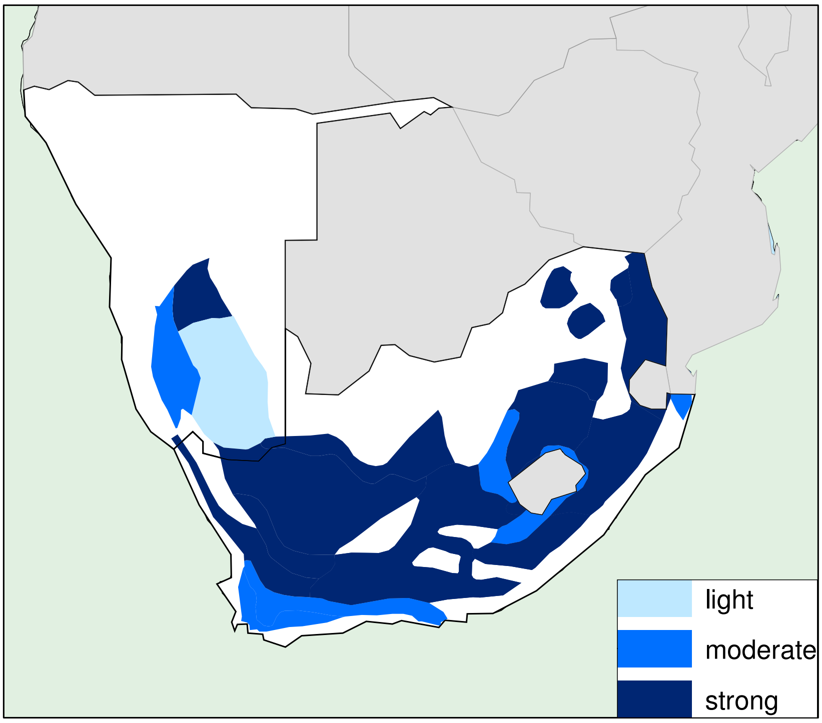

Fig. 3.4: The extent of soil degradation due to water erosion in Namibia and South Africa. Data by GLASOD (Oldemann *et al.*, 1991)

ments, in particular the Betterment Areas Proclamations 31 of 1939 and R196 of 1967 governed by the Department of Native Affairs and applicable for reserve inhabitants. Soil conservation efforts comprised contour banks, grass strips and fencing, but also the introduction of carrying capacity numbers and, as a consequence, radical lifestock reductions by culling. On the other hand, erosion was not a problem on communal lands alone, therefore the Soil Conservation Act no 45 was legislated in 1946 that was administrated by the Department of Agriculture and binding for white commercial farmers. In contrast to the punitive concept of the Department of Native Affairs, white farmers were granted loans and subsidies for undertaking approved conservation work on their land. However, although conditions for sustainable and soil conserving land use were much more favourable for white farmers, they also struggled under the pressure to make South Africa self-sufficient in terms of food generation whilst at the same time striving for economic survival and profit (Garland *et al.*, 1999).

These acts and proclamations were later backed up by subsequent colonial and apartheid legislation and led to several consequences within the homelands as summarized by Garland *et al.* (1999)

- increasing cultivation of unsuitable land (less fertile and more erodible soils such as fields on steep slopes) due to high population densities in the homelands
- ecologically excessive dependence on grain crop monoculture

- subsistence survival strategies and labour shortage due to a high degree of migrant workers preventing sustainable agricultural intensification
- poor or politically unaceptable agricultural extension advise, insensitively delivered and commonly rejected
- technically inappropriate soil conservation programmes
- a coerced land-use system incorporating the "Tragedy of the Commons"

The role of the land-use system itself is subject to controversial discussion. Classically, commercial land tenure is regarded as more suitable in terms of sustainable land management than communal land use. The decisive difference is largely seen within the so-called "Tragedy of the Commons" (Hardin, 1968), a socio-ethic paradigm that describes the conflict between individual demands and the common good as a finite resource. In the case of land tenure this means that communal lands, whether in Southern Africa or elsewhere, are doomed to over-utilisation since nobody will take over responsibility for land that he does not personally own. Undeniably, degradation is more frequent and also often more severe in commonages than on commercial farms. Nevertheless, some publications have shown that this is not always the case; Ward *et al.* (1998) found no difference in a number of soil and vegetation parameters between communal areas and commercial farms in Otjimbingwe in south-central Namibia, nor did Ward *et al.* (2000) in Okondjatu, north-east Namibia; Hongslo & Benjaminsen (2002) venture further by analysing the narratives and counternarratives in interviews held with Namibian commercial and communal farmers. According to their research, it has to be considered whether degradation is rather a function of erratic rainfall and resilient environment (communal farmers concepts) rather than overgrazing (commercial farmers perception).

Apart from land-use, climate change is regarded the second key factor causing degradation in Southern Africa. Evidence is given that already changes have been taking place in terms of increases in the intensity of extreme rainfall events (Mason *et al.*, 1999). The impact of temperature changes is also likely but difficult to identify since it is entangled with other factors such as land-use effects; it is therefore not clear, which factors account for detected changes. However, research results from the northern hemisphere clearly indicate changes and suggest similar trends in other parts of the earth (Thuiller, 2007).

Varying global change scenarios, all based on applications of General Circulation Models (GCMs), predict generally drier climates for Southern Africa, increased rainfall variability, increased summer rainfall and reductions of precipitation in winter rainfall areas, increases in heavy rain events (> 20 mm/d) and consequently, increases in the severity of flood events, as reviewed by Meadows (2006). Admittedly, these scenarios and predictions hold incertainties but it is widely agreed that the trend is valid. As a consequence, shifts in species' geographical range are expected. Thuiller (2007) states that each 1°C of temperature change of a predicted rise by up to 4°C by 2100, moves ecological zones on Earth by about 160 km. Hannah *et al.* (2002) modelled the distribution of South African biomes; according to this model, South African biomes with high biological diversity will shrink to about half of their current distribution with the almost complete displacement of the Succulent Karoo Biome and a marked eastward relocation of the Nama-Karoo. At the same time, the extent of deserts will increase.

The increase in atmospheric CO_2 concentrations is discussed to have marked effects on savannas due to a shift of the competitive balance towards woody species in relation to grassy ones. The "CO_2-fertilization" of the atmosphere leads to enhanced photosynthesis rates - plants with deeper rooting systems and better drought resistance will be favoured. The degradation of rangelands by shrub encroachment, already a severe and widespread problem in Namibian savannas, is therefore likely to aggravate in future.

4 Small Scale Variability of Topsoil Properties and its Significance for the Succulent Karoo Ecosystem

4.1 Introduction

The BIOTA Observatory No 22 Soebatsfontein is situated in the northwestern part of South Africa, approx. 30 km east of the Atlantic coast line, 65 km southwest of the city Springbok and 35 km west of the small town Kamieskroon. Geographically, the site is part of Namaqualand, an area of roughly 50,000 km^2 in extent, ranging from the Olifants River in the South to the Orange River in the North and the bushmanland plains in the East. The Namaqualand roughly covers the winter rainfall region of the Succulent Karoo biome and extends further to the Cape, the Nama Karoo of Namibia and the Karoo landscapes to the East.

The observatory covers an altitudinal range between 261 and 434 masl; as the digital elevation model indicates (Fig. 4.4), it is characterised by a high outcrop ridge, its smaller western flank and its wider easterly exposed slopes. Watkeys (1999) refers to this area west of the great escarpment as the *west coast*; Hoyer (2004) describes the territory as a transition between the great escarpment and the coastal zone. However, locally, the region is known as *hardeveld* (Cowling *et al.*, 1999a).

The observatory is part of the commons of Soebatsfontein, a village with approx. 270 inhabitants 8 km beeline to NNW. The communal farmland with a total of 15,069 ha (Department of Landaffairs. Republic of South Africa, 2001) was only transferred to the community in 2000 in the context of the national land reform programme after the apartheid-regime had stood down and South Africa faced the challenge of redressing the unequal and racialist land distribution of the past (May & Lahiff, 2007). Today, the farmland is divided into camps and managed by the the commonage method to ensure that each of the families has the opportunity to make a viable living from farming (Department of Landaffairs. Republic of South Africa, 2001). Decisions regarding management rules are made by the Soebatsfontein Commonage Committee. Since the community members are aware of the uniqueness of the landscape, they strive towards sustainable management practices (Schmiedel, 2006).

It is assumed that the high degree of biodiversity occurring in Namaqualand is linked to a high degree of habitat differentiation and thus to a rich pedodiversity as a main factor. The work of Petersen (2008) affirms this statement.

By structuring the observatory into nested scales and creating a data base involving topsoil samples of micro units, differentiated in fine layers, a basis is created for the small scale analysis of topsoil properties and the clarification of the following key questions:

- Is there a high variability of topsoil properties on the observatory?
- Are the significant differences on the small scale between open soils and soils that are affected by microfeatures such as biological soil crust and shrubs?
- To which extend does microtopography contribute to variability?
- To which extent do patterns and scales contribute to overall variability on the observatory?

4.2 Characterisation of the study site

4.2.1 Geology and Geomorphology

An elaborated summary of the geologic and palaeoenvironmental history of the Namaqualand is given by Meadows & Watkeys (1999).

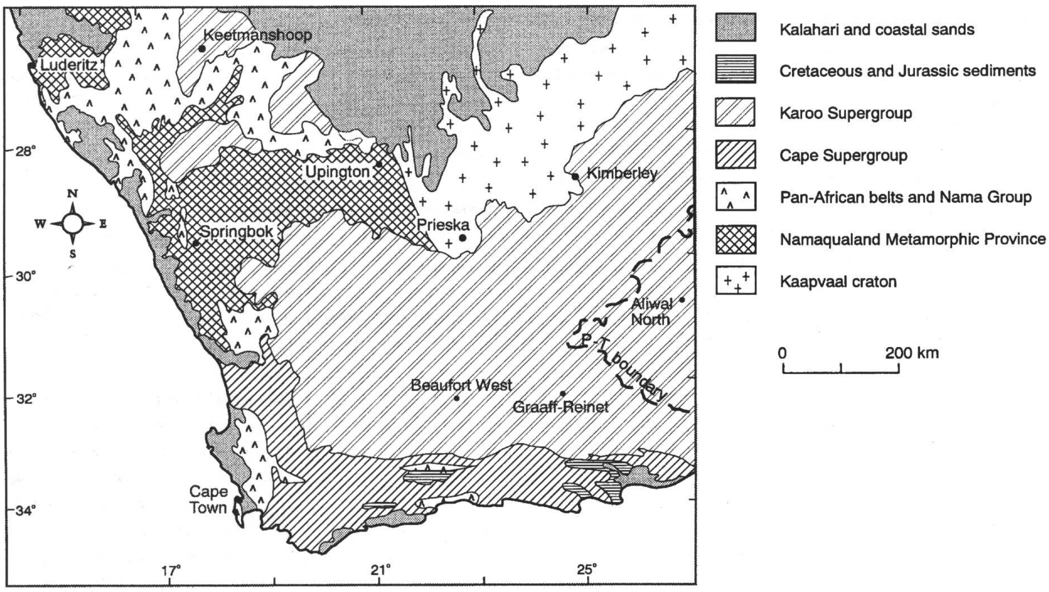

Fig. 4.1: Geological overview of Namaqualand. (Source: Meadows & Watkeys (1999))

Due to the complex genesis of the Southern African landsurfaces, the bedrocks and parent materials for soil development in Namaqualand are manifold in character. The northern mountaineous area of Namaqualand, the Richtersveld, consists of varying pre-Gondwanan rocks that are intensively intruded by granites and gneisses of the Namaqua Metamorphic Province and form a complex array of bedrocks (Willer, 2004). To the South, the mountains of the Great Escarpment attach to the Richtersveld, and separate the coastal zone from the plains of the interior plateau. The highest peaks of the "hardeveld", at the Kamiesberg, range between 1,200 and 1,700 m; to the West the hardeveld merges in lowland plains that are broken by numerous ridges and rocky hills (”koppies”, rising up to 700 m amsl), remnants of the eroded Great Escarpment (Partridge, 2004). Here, the BIOTA Observatory Soebatsfontein has been established. The dome-shaped outcrops of the Namaqua Metamorphic Complex are landscape forming features and were classified by Jack (1980) as streaky gneisses. According to this author, the rocks consist of 30% quartz, 40% K-feldspar, 20% Plagioclase and 10% biotite. Sphene and Opaque occur as trace elements. Faults and shear zones within the gneiss are commonly associated with quartz veins. Between the rocky outcrops, valleys and plains consist of tertiary and quaternary colluvial sediments enriched with airborne sand (Watkeys, 1999; Hoyer, 2004). Further seawards, complex sequences of marine and windblown sands compose the coastal zone of Namaqualand. The main sediments are formed by weathered and fine-grained deposits of the Late Tertiary and white and calcareous sands of recent times (Watkeys, 1999; Cowling *et al.*, 1999a). The southern part of Namaqualand ends in the so-called Knersvlakte, an area consisting of various exceptionally large quartz fields, covered with white, angular quartz debris (Schmiedel & Jürgens, 1999).

4.2.2 Climate

Two weather systems dominate the climate in Namaqualand: the southern subtropical highpressure (anticyclone) belt and, more to the south, the circumpolar westerly airstream (Preston-Whyte & Tyson, 1988). Since the zenith is oscillating interannually between the tropic of cancer and the tropic of capricorn, the southern subtropical highpressure belt is consequently moving between northern and southern hemisphere. This leads to warm and dry southern summers under the influence of the south tropical highpressure belt with south-easterly warm and dry winds. In winter, when the circumpolar westerly airstream is moving northwards, cold fronts occur as a result of major disturbances in the westerly air stream that are characterised by northerly winds and cloud-free conditions ahead of the front and widespread rain (in higher positions even snowfall) and low temperatures at its rear (Desmet & Cowling, 1999b). The winterly cold fronts account for most of the annual rainfall which is highly reliable. In addition, winterly coastal lows, generated through localised cyclonic vorticity as a result of the westward movement of air of the high plateau, may produce orographic mist and fine drizzle at the coastal margins.

The reliability of rainfall is based on the fact that in southern Africa, the equatorwards penetration of the westerly airstream is greatest among all continents (Preston-Whyte & Tyson, 1988). Based on comparisons of the co-efficient of variation (CV) as a measure for rainfall variability, reliability of rainfall in the winter rainfall Karoo was calculated as 1.15 times more compared to the adjacent, summer rainfall dominated Nama Karoo (Desmet & Cowling, 1999b). However, mean annual rainfall varies strongly on a regional basis; it ranges between 50 mm in the northwestern part of Namaqualand and 400 mm in the Kamiesberg area (Cowling *et al.*, 1999a). In Soebatsfontein, mean annual rainfall matches approx. 130 mm (BIOTA weather data, see Fig. 4.2).

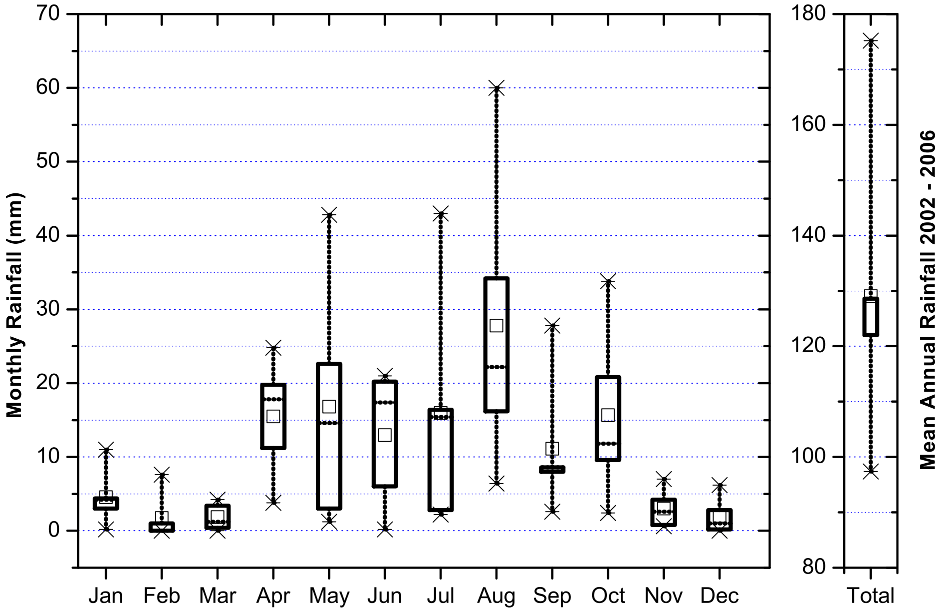

Fig. 4.2: Monthly and annual rainfall at Soebatsfontein 2002 – 2006 (Source: www.biota-africa.org).

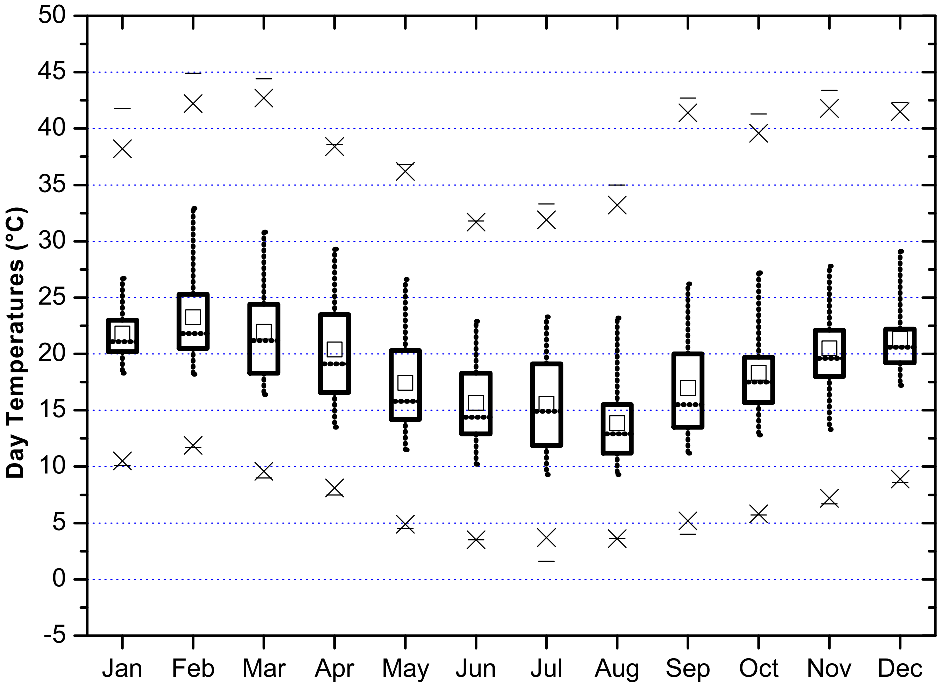

Fig. 4.3: Mean, maximum and minimum day temperatures at Soebatsfontein 2002 – 2006 (Source: www.biota-africa.org).

Important alternative sources of moisture for plants in the arid Karoo biomes are advective sea fog and dew. Sea fog develops in near-surface air layers over the cold Benguela current nearby and reaches 50 - 75 km inlands (MacKellar *et al.*, 2007). Dew is widespread due to high humidity and relatively cool noctural temperatures in the region (Cowling *et al.*, 1999a).

Namaqualand has also been characterised as a relatively mild desert due to the proximity to the cold, upwelled waters of the Benguela Current which are tempering extreme temperatures (Cowling *et al.*, 1999a). Mean temperatures therefore range from 14 °C in winter and 23 °C in summer (BIOTA weather data, see Fig. 4.3). Remarkably, in contrast to the readings from 2002 - 2006 on the observatory, high temperatures up to 40°C are reported to occur in Namaqualand in winter, when hot so-called "bergwinds" descend coastwards from the high altitude plateau of southern Africa (Cowling *et al.*, 1999a).

4.2.3 Vegetation

Namaqualand as part of the Succulent Karoo biome belongs to the winter rainfall area of Southern Africa. The Succulent Karoo itself ranges over an area of 103,000 km^2 and inhabits 4,849 plant species, 40% of which are endemics (Hilton-Taylor, 1996). According to recent publications, this flora is part of the Cape Floral Kindgom and now referred to as the Greater Cape Floral Kingdom (Born *et al.*, 2007). The Succulent Karoo is one of two desert regions recognised as a global biodiversity hotspot, as determined by Myers *et al.* (2000) due to their species diversity and endangerment. Namaqualand, comprising a quarter of the area of the Succulent Karoo, accounts with 3,500 species to the biological diversity with 25% being endemic (Desmet, 2007). This diversity is not evenly distributed but concentrated in local centres of endemism such as quartz fields of the Knersvlakte, the Richtersveld and the Kamiesberg area.

The vegetation structure can generally be described as shrublands dominated by small plants such as small leaf-succulents and geophytes, which provide over 50% of the flora (Desmet, 2007). According to the recent vegetation atlas of South Africa (Mucina & Rutherford, 2006), two vegetation types occur in the Namaqualand hardeveld bioregion where the observatory is situated: the Namaqualand Klipkoppe Shrubland and the Namaqualand Heuweltjieveld. 278 species were found on the observatory Soebatsfontein (U. Schmiedel, pers. communication), which encompasses only 1 km^2, making it one of the observatories with the highest floral diversity along the BIOTA transect. Common plant species are *Ruschia cyathiformis* and *Cephallophyllum inaequale*.

Different publications have revealed, that under heavy and prolonged grazing, the typical perennial vegetation of Namaqualand landscapes shifts to a more annual and geophyte dominated herbland (Palmer *et al.*, 1999, and references therein). Interestingly, the ephemeral community that replaces the shrubland is equally diverse in terms of species numbers, and the composition is almost entirely made up of species indigenous to Namaqualand (Todd & Hoffman, 1999). Desmet (2007) concludes, that the vegetation of Namaqualand is adapted to intense grazing/ disturbance with a large component of the flora being adapted specifically to taking advantage of disturbances. Disturbances caused by large grazers such as springboks can most likely be excluded since their numbers were low and their occurrences too erratic to execute such a significant evolutionary pressure (Hoffman & Rohde, 2007). Instead, the author refers this phenomenon to the ubiquitous heuweltjies that are characterised by their deep and fine textured soils and higher nutrient contents that attract digging animals such as rodents on the one hand and, because of the more palatable fodder plants, also grazers on the other hand. One of the causes for the high degree of floral biodiversity is seen in this coexistence of vegetation mosaics (disturbance vegetation and climax vegetation); others are the frequent but low volume rainfall events that are moreover occurring during the winter months when evaporation is low, the complex physical environment and a diverse fauna.

4.2.4 Landuse History and Utilisation

As summarised by Webley (2007), good archaeological evidences exist that Namaqualand is subject to pastoralism for already up to 2000 years. The development of human population, livestock and cultivation in Namaqualand with the onset of colonialisation is described by Hoffman & Rohde (2007).

When first European settlers arrived in the Cape in the 17th century, they reported an indigenous pastoralist population that occupied a large part of the coastal margins of western South Africa. Those tribes were described to be sparcely distributed across the landscape and to possess vast herds of cattle and flocks of sheep. The Khoekhoen tribal grouping that inhabitet the region north of the Olifants River, called themselves the little Namaqua. Further historical sources report that these people followed a seasonal transhumance cycle between the Kamiesberg and the low-lying coastal plains; during the sommer months (November - March) they moved to the Kamiesberg and aggregated at permanent waterholes. However, in the winter months (April - October), temperatures in the highlands were severe and endangering man and livestock, especially lambs which are born in that time, so that the tribe travelled with their herds to the more convenient lowlands. No data exists on the numbers of livestock during that time, but the authors conclude from the lifestyle of the Namaqua that livestock numbers were low since the pastorlists needed a "manageable" herd size for their migrations between various ecological zones.

In about 1750, first European farmers settled in Namaqualand; they did not only introduce cultivation but also epidemics such as the smallpox that decreased the Namaqua population down to a number of only 400 people by 1779. Nontheless, in the following years, population numbers in Namaqualand increased rapidly by recovery of the Namaqua population but also through additional trekboers and runaway slaves so that by the early 1800s the Khoekhoen pastoralists felt urged to seek protection for their traditional grazing lands from the church to avoid further occupation and possession by white farmers. These areas later became the six Coloured Rural Reserves in Namaqualand (Hoffman *et al.*, 2007). In the same time, the Namaqua adopted the cultivation of the white farmers and took over a more sedentary lifestyle. Main crop was wheat, with smaller amounts of oats, barley and rye. These fruits were cultivated in the low-lying areas with deeper soils whilst the rocky upland environments stayed untransformed.

From that time, population and agricultural utilisation increased in Namaqualand. From a first census in 1865 for the newly created Namaqualand District untill 1910, population doubled from 10,000 to 20,000 inhabitants; cultivated land increased in the same time from 5,000 ha to 15,000 ha, the number of sheep from 100,000 to 200,000 animals and the number of goats approximately trippled from 50,000 to 150,000 animals. In addition, about 20,000 cattle were grazing on the rangelands.

In the mid of the 20th century, landuse in Namaqualand changed significantly; commercial farms were fenced into camps, communal areas were enclosed. White commercial farmers were promoted through state subsidies, stock reduction schemes, state infrastructure grants and drought relief programs. For communal areas, livestock carrying capacities were calculated and surplus animals above the estimated value culled (Benjaminsen *et al.*, 2006). Nevertheless, up to today stocking densities are double in communal areas compared to commercial farms (Hoffman *et al.*, 1999).

As a whole, agriculture still increased and formed a peak with regards to cultivated land and sheep numbers in the 1970ies. But then a change took place: the percentage of rural inhabitants decreased from 50% in 1970 to 9% in 1991. Cultivation decreased from 29,000 ha in 1971 to 11,600 ha in 1988 with an ongoing trend. The continuing de-agrarianisation and decline of rural population is a consequence of national and global economic conditions, improved transport networks and the cessation of agricultural subsidies. Simultaneously, conservation initiatives increased, and a significant proportion of privately-owned, commercial sheep farms was acquired by the state and redistributet as grazing commonage with the purpose of alleviating the crowded conditions in Namaqualands communal areas (May & Lahiff, 2007). According to (Hoffman *et al.*, 1999) those communal areas make up 25% of Namaqualand .

The commonage of Soebatsfontein, which was handed over to the community in 2000, formerly belonged to the De Beers mining company. By that time, the rangeland was partly in a rather bad condition (Schmiedel, 2006), a result of enduring high stocking densities in the past (Anderson, 2004). Also, areal photographs give evidence of a former field at the food of the eastern slope on the observatory; however, more detailed information about the cultivation history is not available.

Today, the farmland of Quaggafontein which is about 1,500 ha in size, is used for rotational sheep and goat farming. Stocking densities on the lands are below the recommended stocking rates of 12 ha/SSU. Since only a third of the households in the community kept livestock, the stocking rate in 2001 was calculated as 38% of the given carrying capacity (Schneiderat *et al.*, 2002).

4.2.5 Soils

Soils of the hardeveld in Namaqualand are derived of the weathered material of the granite-gneiss outcrops that belong to the Namaqualand-Metamorphic complex. On the rocky hills themselves, in-situ weathering products of the outcrops were extensively eroded; however, undifferentiated and free-draining sandy- to loamy soils are found in rock pockets, crevices and in less exposed, stronger sheltered areas. On the slopes and plains the debris of quartz veins within the granites leads to small areas of quartz fields. Otherwise, deeper granite-derived colluvial soils are dominant that might also be enriched with airborne sands and silt. Those soils are reddish in colour and of loamy texture (Watkeys, 1999). However, the plains have to be differentiated into two units; the main "matrix" soils and the "heuweltjie"-soils that make up approx. 25% of the area where they occur (Lovegrove & Siegfried, 1989). The heuweltjie soils differ significantly from the matrix soils by higher silt contents and enrichments in Ca, Mg, K, P, Mn and N, thus creating a distinct vegetation community on-mounds compared to interheuweltjie-areas (see chapter 3.3.4). Of equal importance is the occurrence of silicic and carbonatic crusts; according to Ellis (2002), heuweltjie mound soils in semi-arid environments are characterised by a central petrocalcic (calcrete) to petroduric (duripan) hardpan, with a petroduric horizon on a petrocalcic horizon towards the outer edge and also in the surrounding inter-mound areas. These exhibit some ecological significance, namely water fluxes and redistribution of this resource. On the leeward side of the ridges, heuweltjies are often covered by sediments and might therefore not be visible at first glance.

Petersen (2008) observed the soil units of the observatory Soebatsfontein based on a two-qualifier level of the WRB (1998) system (ISSS-ISRIC-FAO, 1998). Dominant soil units on the square kilometer are Durisols and Cambisols, the former being exclusively associated with the occurrence of heuweltjies and their underlying hardpans while the latter are found in inter-heuweltjie areas on deeper substrates. Most interestingly, Petersen (2008) also reports of the occurrence of Mollic Cambisols that qualify by a thick ($>$ 10 cm) horizon with high contents of organic carbon ($>$0.6 %) and a high nutrient status (base saturation $>$ 50%). These soils are developed below exposed bedrocks where they receive run-on water on the one hand and debris and nutrients as weathering products of the rock surface that is intensively colonised by lichens on the other. However, these soils are rare on the observatory and a unique exception in drylands in general. More frequently, Petersen (2008) mapped Leptosols and Regosols, predominantely developed on the higher, rocky areas. Further, enrichment of soluble salts and calcium carbonate qualify the soils of some heuweltjie positions as Solonchaks and Calcisols. Data on the soil inventory of Soebatsfontein are published in the internet (www.biota-africa.org).

4.3 Description of Sampled Units in a Hierarchical System

According to the scaling concept described in 2.2.2, the study site was subdivided in nested units belonging to four different scales. On five D2 areas, seven small scale study-sites where established covering the most abundant D3 units, ranging in size between 25 and 110 m^2. The chosen D2 sites and their D3 units are characterised as follows:

- *Lower Eastern Slope with heuweltjies (ES)*: Situated on the eastern flank of the mountain, this unit is characterised by its mosaic of deep soils and heuweltjies. It comprises the plains as well as the slightly more inclined lower slope. Its geomorphological border was determined as the zone further uphill where smooth outcrops start to protrude the surface. The unit consists of the D3 areas heuweltjie centre, heuweltjie margin, (interheuweltjie-) matrix soil and quartz fields. Study sites were established as a transect from a heuweltjie top to the matrix as well as within a quartz field.
- *Accumulation Zone within Lower Eastern Slope(AC)*: The Accumulation Zone is an area embedded on the Lower Eastern Slope though clearly distinct due to its more sandy, more homogeneous soils and its different vegetation; the heuweltjies occuring here seem to only partially protrude out of the matrix. The origin of this peculiar area is not clear; however, two hypotheses have been formulated in this regard that may apply separately or combined: 1) the area is a formerly cultivated field. The somewhat quadrangular form visible on aerial and satellite photos militates in favour of this idea as well as reports of the villagers that there are abandoned fields in the commonages. However, no evidence is given if this holds true for this particular site; 2) the area is based below a deep erosion gully at the foot of the mountain. Thus, the study site might be located in an area where sediments of higher situated areas are washed in and covered the heuweltjies to a certain degree. D3 units are heuweltjie centre, heuweltjie margin and matrix soils.
- *Mid-Eastern Slope (MS)*: The Mid-Eastern Slope is located on the eastern slope of the observatory with an inclination of approx. 25%. It was defined as the middle part of the eastern slope where smooth granite boulders alternate with shallow to deep soil patches. Heuweltjies do also occurr here, but to a slightly lesser extent. This unit is bordered to the west by the more mountaineous upper slope with its enormous rock boulders and downslope by the ”Lower Eastern Slope” unit with its deeper soils. D3 units consist of different matrix soils and areas right below the rocks that are expected to be zones of nutrient and water accumulation, in the following termed as rock fringes.

- *Western Slope (WS)*: This slope is exposed seaward and its inclination roughly comparable to the Mid-Eastern Slope. Boulders are missing; heuweltjies do exist although they are eroded and covered to such an extent that they are only distinguishable by their colour and vegetation from the adjacent slope. Thus, the definition of the D3 units Heuweltjie Centre and Heuweltjie Margin was more difficult than on the Lower Eastern Slope. The matrix between the heuweltjies often shows eroded structures which are stretching in parallel lines more or less transversally across the site. The surface is rather smooth and more level than other units, the soil is tough and crusted. It seems that runoff generates and drains along these streaks. Two study sites were established on the Western Slope: one as a transect from a heuweltjie top to a heuweltjie margin, and one within the matrix area.
- *Mountain Top (MT)*: The Mountain Top unit is similar to the Mid-Eastern Slope in terms of its mosaic of alternating rocky outcrops and soils of different depths. In contrast to the Mid-Eastern Slope, however, rocks occur as high boulders as well as smooth outcrops that have approximately the level of the soil surface around them. In addition, very shallow soil patches have been found on the smooth rocks that inhabit small succulent plants, termed as rock crevices. D3 units that have been defined on the respective study site are different matrix units, rock fringes and rock crevices.

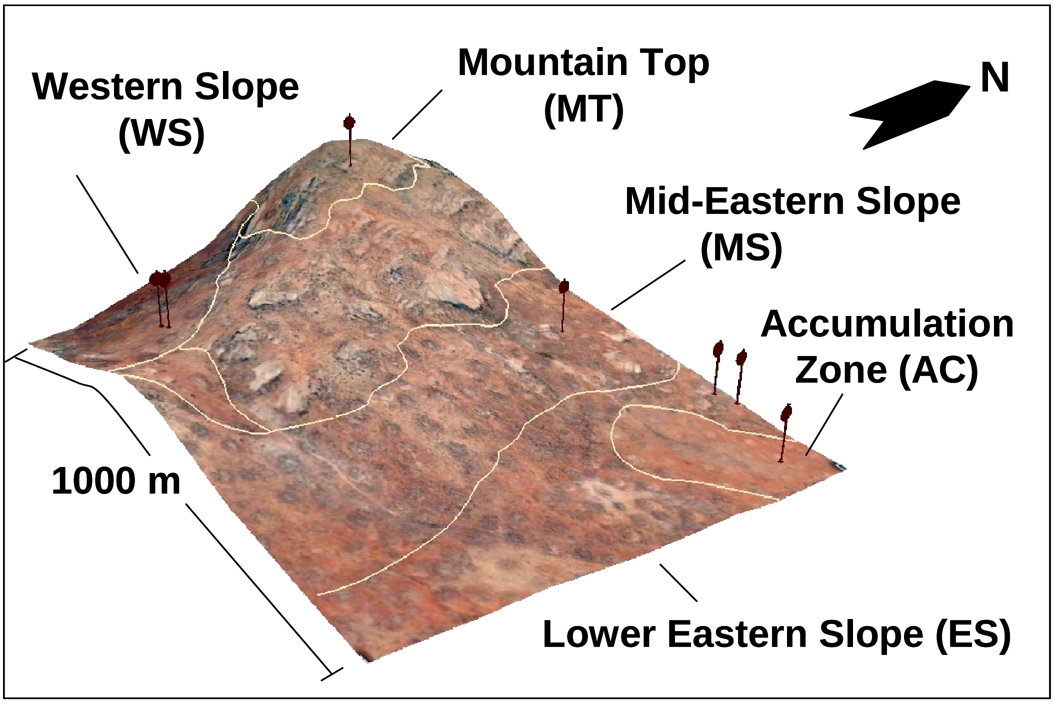

Fig. 4.4: Digital elevation model of the Soebatsfontein Observatory and location of study sites within D2-units (Source of satellite picture for DEM: Google Earth ©).

On the complete observatory, only four D4-units were defined. Those are:

- open soil (O)
- soil below plant canopies (P)
- soil below dead shrubs, so-called "safe-sites" (D)
- soil covered with biological soil crusts (B)

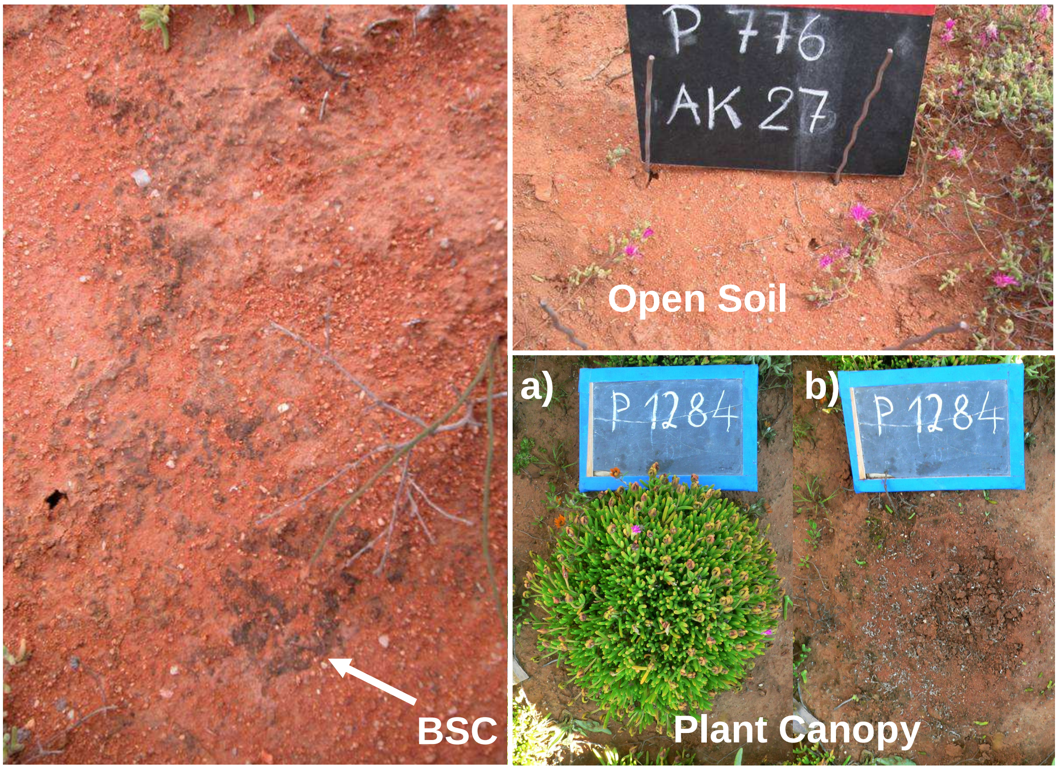

Fig. 4.5: Examples for D4 units Biological Soil Crust (BSC), Open Soil and Plant Canopy in Soebatsfontein. The last is shown before (a) and after (b) preparation for miniprofile sampling (photos of plant canopies by G. Miehlich, 2006).

It has to be noted that not all D4 units occurred on all study sites. Therefore, to gain a sample number that is still processable, only the most significant D4 units were chosen for sampling.

After the definition of units and the establishment of the study sites, high resolution tachymetric surveys where conducted on each site. Apart from the microtopography, the survey included determination of the distribution of perennial plants and the location of test and sampling sites. Topsoils where sampled on D4 units in five parallels and three layers according to the miniprofile procedure as described in Chapter 2.2.3. In addition, on each D3 unit, a deep reference profile was dug and sampled. A table of the sampled units is given below:

D1: BIOTA Observatory 22 Soebatsfontein	D2	D3	Abbr	D4	Abbr	Abbreviation
	Lower Eastern Slope (ES)	Heuweltjie-Centre	HC	Open Soil	O	**ES-HC-O**
				Plant Canopy	P	**ES-HC-P**
				Dead Shrub	D	**ES-HC-D**
		Heuweltjie-Margin	HM	Open Soil	O	**ES-HM-O**
				BSC	B	**ES-HM-B**
				Plant Canopy	P	**ES-HM-P**
				Dead Shrub	D	**ES-HM-D**
		Matrix 1	MA1	Plant Canopy	P	**ES-MA1-P**
		Matrix 2	MA2	Open Soil	O	**ES-MA2-O**
				BSC	B	**ES-MA2-B**
	Accumulation Zone (AC)	Heuweltjie-Centre	HC	Open Soil	O	**AC-HC-O**
				BSC	B	**AC-HC-B**
		Heuweltjie-Margin	HM	Open Soil	O	**AC-HM-O**
				BSC	B	**AC-HM-B**
		Matrix	MA	Open Soil	O	**AC-MA-O**
				BSC	B	**AC-MA-B**
	Mid-Eastern Slope (MS)	Matrix1	MA1	Open Soil	O	**MS-MA1-O**
				BSC	B	**MS-MA1-B**
		Rock Fringe	RF	Open Soil	O	**MS-RF-O**
		Matrix2	MA2	Open Soil	O	**MS-MA2-O**
	Mountain Top (MT)	Rock Fringe 1	RF1	Open Soil	O	**MT-RF1-O**
				Plant Canopy	P	**MT-RF1-P**
		Matrix 1	MA1	Open Soil	O	**MT-MA1-O**
		Matrix 2	MA2	Open Soil	O	**MT-MA2-O**
				Plant Canopy	P	**MT-MA2-P**
		Rock Crevice	RC	Plant Canopy	P	**MT-RC-P**
		Rock Fringe 2	RF2	Dead Shrub	D	**MT-RF2-D**
	Western Slope (WS)	Heuweltjie Centre	HC	BSC	B	**WS-HC-B**
				Plant Canopy	P	**WS-HC-P**
		Heuweltjie Margin	HM	BSC	B	**WS-HM-B**
				Plant Canopy	P	**WS-HM-P**
		Matrix	MA	Open Soil	O	**WS-MA-O**
				BSC	B	**WS-MA-B**

Tab. 4.1: Soebatsfontein: Scheme of nested units

4.4 Results and Discussion

4.4.1 Soilchemical Properties on the Observatory Soebatsfontein: an Inventory

4.4.1.1 Comparison of Chemical Soil Parameters with the BIOTA Transect Data Set

The total data set of the observatory was analysed with regard to the distribution of the single parameters and compared with the parameter distribution compiled for the whole BIOTA-South data set (www.biota-africa.org). The transect data are described in detail in Petersen (2008). Here, the data is used to highlight the specific characteristic of topsoil properties in Soebatsfontein.

The values of specific soil parameters on this single observatory varied widely; for example, the pH_{H2O} ranged on the Soebatsfontein observatory nearly to the same degree as on the whole transect. The data distribution, however, indicates a tendency of the soils to more alkaline conditions. The EC ranged between 18 and 3450 μS/cm; this is less than the range of the BIOTA transect data, which contains the values of 4000 samples among which some were situated on extreme sites. Nonetheless, the variability of the EC is to be assessed as large. Also, median and quartiles show that the occurrence of increased salt contents is more abundant in Soebatsfontein than on the transect scale. This is further confirmed by Na_t, Cl_{we}, Na_{we} and the anions_{we} and $\mathrm{cations}_{we}$ values that show strikingly higher median values and 75 quartiles relative to the comparative data set.

Further noticeable parameters are the K-species: K_t, K_{we} and K_{dl} that show exceptionally high values. So are Zr_t. P_t and Pb_t increased on this site disregarding the extreme maximum values occurring on the transect. The distribution of Mn_t and Fe_{we} slightly shifts to high values, indicating that commonly higher Mn_t values occur compared to the transect distribution.

Miniprofile Data 22 Soebatsfontein									Transect Data								
Parameter	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**	**Parameter**	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**
pH$_{H2O}$	493	4.4	6.5	8.0	7.8	9.1	10.4	1.5	**pH$_{H2O}$**	3,473	3.8	6.2	6.8	6.9	7.8	10.4	1.2
pH$_{CaCl2}$	493	3.9	5.8	7.1	6.8	7.9	8.8	1.2	**pH$_{CaCl2}$**	3,474	3.3	5.3	6.4	6.3	7.2	9.9	1.2
EC$_{2.5}$ (µS/cm)	493	18	69	157	324	330	3,450	461	**EC$_{2.5}$ (µS/cm)**	3,473	1	15	42	364	110	35,300	1,376
EC$_5$ (µS/cm)	493	11	51	112	218	241	2,020	285	**EC$_5$ (µS/cm)**	3,472	2	12	32	229	81	20,300	809
C$_{inorg}$ (%)	308	0.00	0.00	0.04	0.16	0.27	0.83	0.21	**C$_{inorg}$ (%)**	2,194	0.00	0.00	0.01	0.20	0.10	6.39	0.55
C$_{org}$ (%)	493	0.15	0.53	1.07	1.33	1.61	11.47	1.24	**C$_{org}$ (%)**	3,013	0.03	0.17	0.28	0.41	0.46	9.95	0.55
N$_t$ (%)	493	0.02	0.05	0.08	0.10	0.12	0.42	0.06	**N$_t$ (%)**	3,356	0.00	0.03	0.04	0.06	0.09	1.66	0.06
C/N-ratio	493	6.9	9.7	11.8	12.5	15.0	27.4	3.5	**C/N-ratio**	3,007	0.6	6.0	8.2	8.2	9.8	75.3	4.4
S$_t$ (g/kg)	449	0.03	0.17	0.23	0.29	0.35	1.35	0.17	**S$_t$ (g/kg)**	2,994	0.00	0.03	0.08	0.28	0.12	75.24	2.19
Si$_t$ (%)	447	27.2	33.8	34.8	34.6	35.6	39.2	1.8	**Si$_t$ (%)**	2,871	3.0	33.9	36.3	36.6	39.4	46.3	5.0
Al$_t$ (%)	449	4.4	5.5	5.9	5.8	6.2	6.9	0.4	**Al$_t$ (%)**	3,011	0.1	4.0	5.5	5.0	6.5	12.2	2.2
Na$_t$ (g/kg)	449	7.0	10.2	11.9	12.3	13.5	19.2	2.7	**Na$_t$ (g/kg)**	3,010	0.1	2.9	6.0	7.1	9.5	31.3	5.5
K$_t$ (g/kg)	449	29.8	37.2	38.9	38.7	40.7	45.5	2.8	**K$_t$ (g/kg)**	2,957	0.0	17.2	22.6	21.6	28.1	67.0	10.6
K$_{dl}$ (g/kg)	66	0.06	0.19	0.27	0.37	0.54	1.37	0.25	**K$_{dl}$ (g/kg)**	567	0.00	0.00	0.11	0.12	0.18	0.95	0.13
Ca$_t$ (g/kg)	449	2.5	4.4	5.8	8.8	8.7	35.9	7.4	**Ca$_t$ (g/kg)**	3,112	0.0	1.6	4.0	10.1	8.2	148.9	17.0
Mg$_t$ (g/kg)	449	0.8	1.8	2.6	5.1	7.1	18.4	4.6	**Mg$_t$ (g/kg)**	3,092	0.0	1.2	4.4	6.1	8.1	62.2	6.4
P$_t$ (g/kg)	449	0.29	0.38	0.42	0.46	0.49	0.78	0.11	**P$_t$ (g/kg)**	3,114	0.00	0.30	0.37	0.40	0.46	5.49	0.24
P$_{dl}$ (g/kg)	66	0.004	0.020	0.049	0.085	0.127	0.357	0.094	**P$_{dl}$ (g/kg)**	472	0.000	0.000	0.013	0.038	0.050	1.030	0.074
Ti$_t$ (g/kg)	449	0.87	1.94	2.39	2.32	2.72	3.45	0.50	**Ti$_t$ (g/kg)**	3,011	0.23	1.77	2.66	3.10	4.11	20.41	1.93
Fe$_t$ (g/kg)	449	5.7	13.8	18.0	16.9	20.0	24.9	3.8	**Fe$_t$ (g/kg)**	2,930	0.1	11.4	20.2	24.0	33.6	102.4	17.1
Mn$_t$ (g/kg)	449	0.10	0.19	0.28	0.51	0.86	1.31	0.39	**Mn$_t$ (g/kg)**	2,997	0.00	0.13	0.31	0.39	0.47	10.92	0.42
Cr$_t$ (mg/kg)	449	5	17	23	24	29	279	18	**Cr$_t$ (mg/kg)**	3,011	0	23	44	49	58	595	47
Cu$_t$ (mg/kg)	449	0	10	13	13	15	24	4	**Cu$_t$ (mg/kg)**	3,011	0	7	15	20	29	384	19
Ni$_t$ (mg/kg)	449	5	8	11	11	14	46	4	**Ni$_t$ (mg/kg)**	3,011	0	9	18	20	26	250	19
Zn$_t$ (mg/kg)	449	20	34	45	50	67	85	18	**Zn$_t$ (mg/kg)**	3,011	1	22	41	48	74	189	31
Pb$_t$ (mg/kg)	449	22	30	31	32	33	39	2	**Pb$_t$ (mg/kg)**	3,011	0	15	21	20	27	117	10
Ba$_t$ (mg/kg)	449	424	527	569	575	619	746	69	**Ba$_t$ (mg/kg)**	2,996	0	382	521	497	622	9,036	317
Sr$_t$ (mg/kg)	449	66	86	100	105	112	198	26	**Sr$_t$ (mg/kg)**	1,545	1	72	98	105	118	2,162	99
Zr$_t$ (mg/kg)	449	43	427	534	532	639	1,136	172	**Zr$_t$ (mg/kg)**	1,545	0	162	205	218	239	1,219	124

Tab. 4.2: Comparison of statistic measures of dynamic and geologic driven parameters between the miniprofile data set of the observatory Soebatsfontein and the BIOTA-transect data soil data set.

Miniprofile Data 22 Soebatsfontein									Transect Data								
Parameter	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**	**Parameter**	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**
Cl_{we} (mg/l)	201	1	5	32	253	206	3,347	517	**Cl_{we} (mg/l)**	1,629	0	2	6	294	25	34,477	1,517
F_{we} (mg/l)	200	0.00	0.10	0.30	0.38	0.50	2.10	0.38	**F_{we} (mg/l)**	1,461	0.00	0.10	0.20	0.43	0.40	21.90	1.13
Br_{we} (mg/l)	201	0.00	0.00	0.00	0.45	0.50	4.70	0.87	**Br_{we} (mg/l)**	1,479	0.00	0.00	0.00	0.66	0.00	67.90	3.33
NO_{3we} (mg/l)	201	0	2	9	28	27	575	68	**NO_{3we} (mg/l)**	1,577	0	1	7	66	21	12,437	509
NO_{2we} (mg/l)	201	0.0	0.0	0.3	0.9	0.8	25.5	2.2	**NO_{2we} (mg/l)**	1,528	0.0	0.0	0.1	0.9	0.5	59.6	3.0
SO_{4we} (mg/l)	201	1	4	10	75	46	1,429	185	**SO_{4we} (mg/l)**	1,626	0	3	5	105	17	4176	377
HCO_{3we} (mg/l)	160	0	96	215	301	407	2,162	299	**HCO_{3we} (mg/l)**	1,178	0	28	89	147	148	10,609	454
Ca_{we} (mg/l)	201	1	6	18	49	54	547	78	**Ca_{we} (mg/l)**	1,628	0	7	17	66	34	3568	204
Mg_{we} (mg/l)	201	2	8	13	44	31	975	109	**Mg_{we} (mg/l)**	1,627	0	3	7	31	14	1530	112
K_{we} (mg/l)	201	2	17	26	36	43	163	30	**K_{we} (mg/l)**	1,631	0	5	11	19	22	788	32
Na_{we} (mg/l)	201	3	24	61	157	185	1,414	221	**Na_{we} (mg/l)**	1,632	0	1	5	154	33	20,680	828
Fe_{we} (mg/l)	200	0.0	1.8	9.6	16.8	25.3	103.7	18.4	**Fe_{we} (mg/l)**	851	0.0	0.8	4.4	17.6	16.0	418.3	39.5
$Anions_{we}$ (mg/l)	160	0.1	0.4	1.5	10.0	9.9	104.2	18.6	**$Anions_{we}$ (mg/l)**	1,183	0.1	0.3	0.6	14.7	2.9	1,041	55.4
$Cations_{we}$ (mg/l)	160	1.0	2.8	6.4	14.7	18.0	139.6	21.2	**$Cations_{we}$ (mg/l)**	1,181	0.0	1.6	2.7	16.1	6.2	1,100	55.8

Tab. 4.3: Comparison of statistic measures of salt related parameters between the miniprofile data set of the observatory Soebatsfontein and the BIOTA-transect data soil data set.

4.4.1.2 Analysis of Frequency Distributions

Frequency distributions were created for each soil parameter to gain an overview of the kind of data distribution, extreme values and possible outliers.

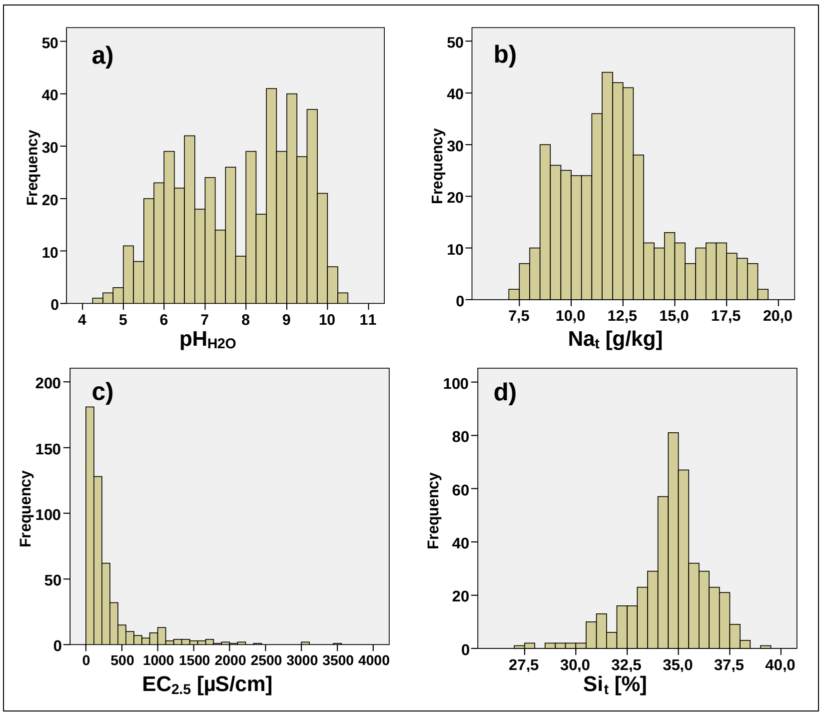

Fig. 4.6: Selected histograms for the miniprofile data set of Soebatsfontein as an example for bi-modal (a,b), skew (c) and normal (d) distributions in the data set.

The histograms were rarely normally distributed, instead, soil properties were often prone to bimodal histograms. Most obviously, this holds true for pH, S_t, Na_t, Ca_t, Mg_t, P_t, Fe_t, Mn_t, Cu_t, Zn_t and Sr_t and indicates that a specific factor or process is impacting on the soil properties dividing them into two groups. Other property groups, especially those indicating any kind of salt occurrence, show a strong skewness to the left. The parameters with the most symmetric distributions are Si_t, Al_t, K_t, Ba_t and Pb_t.

Extreme values (two- to threefold amount of standard deviation) occurred in most properties that were connected to salt accumulation and could be identified as samples on some particular sites which involved rock fringes and heuweltjie soils. There were also some samples that featured exceptional values in terms of parameters associated with organic matter, such as C_{org}, N_t and S_t.

4.4.2 Variability on D3-Scale

Petersen (2008) analysed the taxonomic and parametric pedodiversity on the Soebatsfontein Observatory. His method of analysis deviated from the study at hand, since he followed the BIOTA standard procedure of soil inventory that is based on a different, though similar, stratification and random sampling with prioritisation according to involved habitat sizes (see 2.2.3). However, when describing pedodiversity on a km^2 scale ($\geq$ habitat scale), it deems appropriate to regard the whole soil profile including subsoil layers and to assess it with taxonomical measures. For smaller scale observations, it is assumed that topsoil properties are far more variable than taxonomic units, at least on the microscale (D4). The higher variability of the small scale exhibits a strong ecological significance in addition to the overarching impact of patterns in terms of soil orders and types.

The present study ties in with the previous work of Petersen. In supplementation to his analysis of large scale pedodiversity that includes D1 and D2-units following the nested scheme of the current work, here, dominantly topsoil properties were analysed in high numbers that were complemented by deep reference profiles for each D3-unit and the classification and findings of Petersen (2008). According to his analysis, Soebatsfontein is one of the BIOTA observatories with the highest pedodiversity, a result that was confirmed by all of his classification procedures. As the cause of this diversity he proposes differences of relief within the square kilometer, the occurrence of heuweltjies and climate factors.

Logically, in continuation of the scale-wise investigation of the pedodiversity and soil variability of Soebatsfontein, differences on the D3- and D4-scale are the aim of the following analysis.

4.4.2.1 Finding Main Patterns within D3-units: Cluster Analysis of Total Element and Texture Data

As a first step, a cluster analysis was conducted to differentiate the total data set into groups within which D3 and D4-units were further analysed. For this purpose, total element data was selected as a group representing geologic driven and rather indynamic properties, since it was assumed that more dynamic parameters would vary strongly on smaller scales and therefore mask the main patterns. Total element data used for this purpose included the parameters Si_t, Fe_t, K_t, Na_t and Ti_t.

A hierarchical cluster analysis was generated with the the mean of the five 5-10 cm replicate samples of each D4-group (Fig. 4.7). This layer was chosen since it was assumed that these samples have the best comparability with regard to their parent material. Here, recent deposition of airborne material, excavated substrate from deeper layers or any other disturbances are less pronounced. In addition, texture data of the composite samples of each miniprofile unit were also grouped according to the cluster analysis (Fig. 4.8). The aim of the analyses was to detect whether there are different parent materials contributing to the soil variability on the D1-unit (thus, the observatory), whether or not groups on the chosen D2-unit are homogenous and to identify possible links between them.

The cluster analysis revealed six cluster groups which are briefly characterised below:

Cluster 1 comprises all samples of the D2-unit Western Slope (WS) which are in turn including Heuweltjie Centre (HC), Margin (HM) and Matrix-units (MA), samples of the two Matrix-units on the Lower Eastern Slope (ES-MA1 and ES-MA2) and samples of the Heuweltjie Centre of the Accumulation Zone (AC-HC). The commonality of these D3-units is their localisation on slopes and slightly inclined plains.

Cluster 2 consists only of Heuweltjie Margin (HM) and Heuweltjie Centre (HC) areas of the Lower Eastern Slope (ES)

Cluster 3 is composed of a rather mixed group of the remaining Accumulation Zone area units (AC) and the Mid-Eastern Slope (MS) units. Obviously, these two D2-groups are composed of the same parent material that is e.g. more sandy, less dust enriched material with granite weathering.

Cluster 4, 5 and *6* all comprise samples of the Mountain Top and are grouped according to their position relative to the slope (Matrix 1 (MT-MA1)/ Rock Fringe 1 (MT-RF1) and Matrix 2 (MT-MA2)). One D4-unit is classified in an extra group (Rock Fringe 1, D4 Open Soil (MT-RF1-O)) which is remarkable since it is the only miniprofile group that is separated by clusters on the D4 basis.

On a superior level, the data is divided into two groups; the one containing Clusters 1 and 2 and with that all Western Slope (WS) units, all units on the Lower Eastern Slope (ES) and the Heuweltjie Centre samples of the Accumulation Zone (AC-HC) that is geomorphologically also located on the eastern slope. The second group consists of clusters 3 to 6 and thus included all rocky habitats as well as their relatively fresh deposits.

The texture data for the same layer did not show exactly the same pattern (see Fig. 4.8). However, the overarching clusters of Fig. 4.7 match the clusters of the texture analysis to a large extent; with the exeption of one unit that makes up a cluster of its own, one group is containing all Western Slope (WS) and Lower Eastern Slope (ES) units while the other comprises Mountain Top (MT), Mid-Eastern Slope (MS) and Accumulation Zone (AC) units. Interestingly, in the texture cluster analysis, Accumulation Zone (AC)-units are grouped together instead of being separated into Heuweltjie Centre and Margin/ Matrix units.

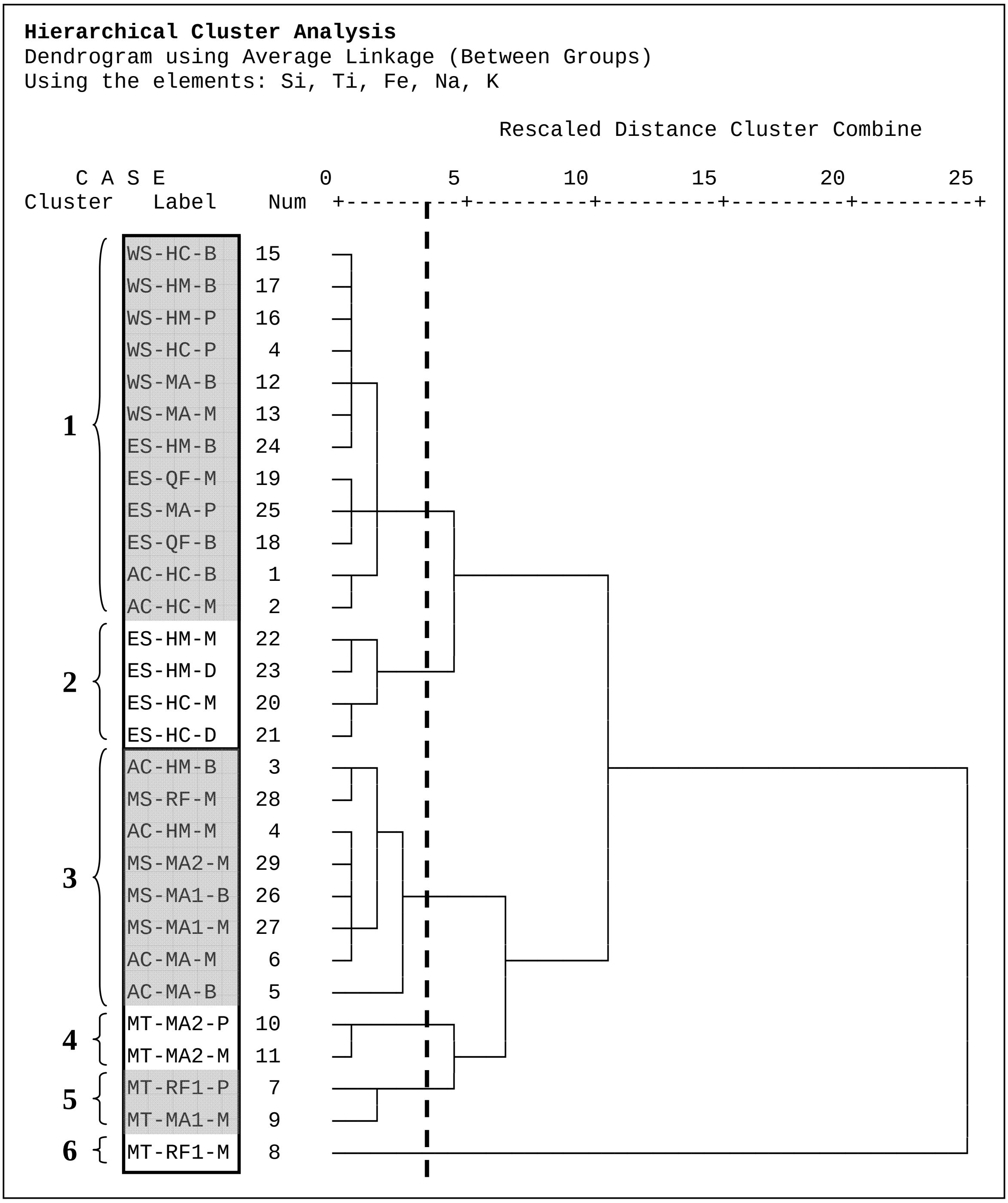

Fig. 4.7: Dendrogram of hierarchical cluster analysis of the mean of five replicate 5-10 cm samples using the parameters Si_t, Fe_t, Na_t, K_t, Ti_t

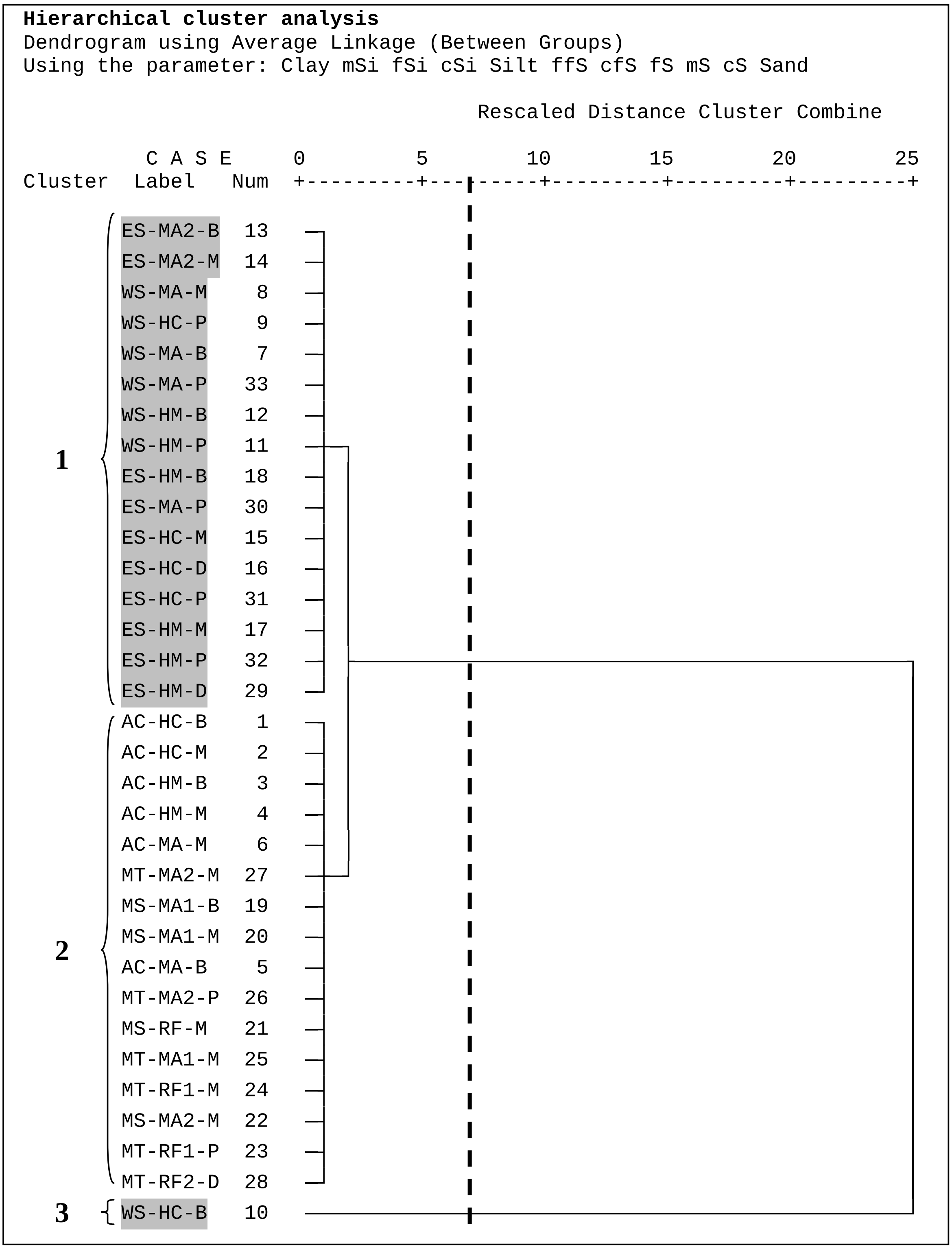

Fig. 4.8: Dendrogram of hierarchical cluster analysis of the mean of five replicate 5-10 cm samples using the parameters Si_t, Fe_t, Na_t, K_t, Ti_t

4.4.2.2 Discussion of Cluster Analysis

The cluster analyses with selected total element contents result in a grouping of two superior clusters: the first group consists of all D3-units on the Western Slope (WS) and Lower Eastern Slope (ES) as well as the Heuweltjie Centres of the Accumulation Zone (AC-HC). The second group consists of rocky habitats and the units of the Accumulation Zone (AC) except the Heuweltjie Centre. This dichotomy is probably based on the incorporation of airborne material which also has an effect on texture, as was shown in Fig. 4.8.

While it proves extensively comprehensible that the D2-units Mountain Top (MT) and Mid-Eastern Slope (MS), both characterised by an alternation of protruding rock boulders, Rock Fringe areas and Matrix soils, are combined to one cluster, the commonality with the Accumulation Zone (AC) is less clear. Moreover, it could have been expected, that this unit would have been rather grouped to the Lower Eastern Slope (ES), since these are located on the same slope and only divided by a distance of approx. 100 m. As a matter of fact, the Heuweltjie Centre of the Accumulation Zone (AC-HC) indeed takes a special position since geologically driven total element contents group differently than texture data. This holds also true for K_t-contents that split the Accumulation Zone units into Heuweltjie Centre (slightly less K_t) and Heuweltjie Margin and Matrix soils, respectively. All in all, the results favour the idea that this area is covered with sediments of the higher situated mountaineous areas. However, this does not exclude the possibility that there also might have been a field, since in such a material agriculture may have been more favourable in comparison to the very patchy, in shallow depths encrusted, unaltered heuweltjie velds.

4.4.2.3 D3-units Generating Variability

Following the results of the cluster analysis, two overarching groups will be analysed more closely with regard to the ecological impact of their D3-patterns. Those are

1. Slopes including Heuweltjie-units with their associated Matrix soils and
2. Rocky Outcrop Areas of which particularly Rock Fringe-units are expected to exhibit a strong influence on variability

D3-Variability on the Slopes: Mutual Dependencies between Heuweltjie- and Matrix-Units Data sets of Heuweltjie-units and adjacent Matrix Areas were available for three D2-Areas, namely the Western Slope (WS), the Lower Eastern Slope (ES) and the Accumulation Zone (AC). Each heuweltjie was subdivided into the units Centre and Margin and sampled correspondingly; on the Lower Eastern Slope (ES) heuweltjie, however, a third unit was considered, which consists of five miniprofiles taken at the transition between heuweltjie and matrix area. Since the foot of this specific heuweltjie was evenly covered with *Cephallophyllum inaequale*, which only left very small open patches between, it was assumed that this creeping dwarf shrub superimposes the comparative value of this unit usually regarded as control. A sampling of the Open Soil unit was therefore not undertaken.

The analysis with Mann-Whitney U tests are presented in Fig. 4.9, Fig. A.2 to Fig. A.15 and Tab. A.1. Main results are as follows: Heuweltjies exhibit a strong influence on soil variability in terms of several parameters. In particular, they lead to significantly increased pH-values with a mean increase of 3.2 pH_{H2O}-units from Matrix (MA) to Heuweltjie Centre (HC) and 3.3 pH_{H2O}-units from Matrix (MA) to Heuweltjie Margin (HM) for the Western Slope (WS), and of 3.2 and 3.5 pH_{H2O}-units, respectively, for the Lower Eastern Slope (ES). This increase of values on Heuweltjie-units compared to the Matrix is also valid for further exemplary tested parameters such as Ca_t, P_t, Mn_t and Zn_t. P_{dl} and K_{dl} which are also increased on heuweltjie sites, though not signficantly due to the low number of available samples. Depending on the D2-unit in focus, these properties are subdividable into those that differ from Matrix on Heuweltjie-Centre and -Margin units alike, and some that only show differences to only one of the Heuweltjie-units. A general valid statement regarding mutual relationships between heuweltjies and soil properties based on the current data alone can hardly be defined. Since in many cases the mentioned parameters show gradients from Heuweltjie-Centre over Margin to Matrix, it seems acceptable to assume that the Centre exhibits the actual impact and the Margins are rather to be seen as transition zones that may be stronger or less affected by Centre properties due to meso- and microtopographical effects such as heuweltjie-slope and disturbances on the micro-scale. This is particularly visible when regarding salt-affected parameters such as EC. On the Accumulation Zone (AC), both Heuweltjie-units have significantly higher EC-values compared to the adjacent Matrix zone. Nevertheless, on the Margin, variability is strongly increased in two out of five miniprofiles that were taken randomly in the vicinity of mole-rat mounds that consisted of the stronger salty soil material from the core of the heuweltjie (compare Petersen (2008) and Reference-Profile P 214, Fig. A.2). On the Lower Eastern Slope (ES), EC-values follow a significant mesotopographical gradient with highest values at the Centre and lowest in the first Matrix-unit (ES-MA1) at the foot of the heuweltjie. The second Matrix-unit (ES-MA2), which is located a few metres further, does not significantly differ from any of the previous three units. Here, a high variability of EC-values was found that is probably connected to the combined influence of the mesotopographical gradient of the heuweltjie and the overarching inclination of the Lower Eastern Slope (ES) itself. The Western Slope (WS) as the third D2-unit in focus shows an opposite trend, though not significantly. Here, a certain hydrological process is assumed that leads to salt accumulations in the Matrix areas around the heuweltjies (see Chapter 4.4.7).

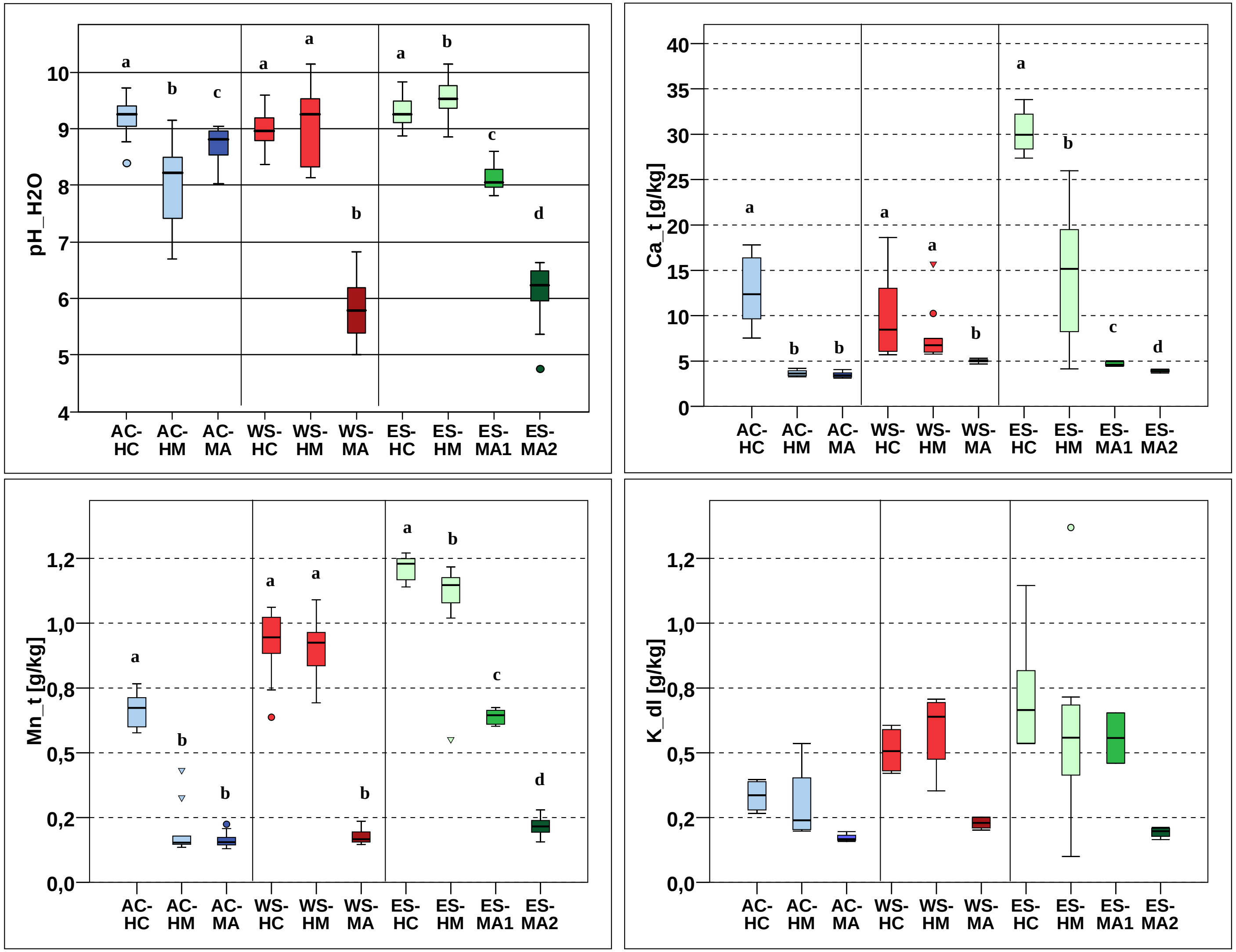

Fig. 4.9: Comparison of Heuweltjie and Matrix-units on D3-scale: Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Accumulation Zone (AC) in blue colours, Western Slope (WS) in red colours, Lower Eastern Slope (ES) in green colours; darker colours designate Matrix-units. Different letters indicate significant differences with p = 0.05.

Furthermore, the analysis revealed a very obvious differentiation between the three heuweltjies themselves. The Lower Eastern Slope (ES) heuweltjie is assumed to be the most typical kind of the three. By contrast, the heuweltjie in the Accumulation Zone (AC) mirrors the D2-specific sedimentation dynamics: sediments generated in higher situated areas were translocated further downslope and accumulated around the heuweltjies. While the Centre parts were left largely unaltered, the Margins were partly affected by the redistribution of sediments. But, apart from that, the Matrix was particularly modified and now consists of materials that are comprised of both, young coarse textured weathering products from the outcrop-areas and mixed-in heuweltjie materials from higher situated zones as well. This oftenly leads to a differentiation of Margin and Center-units in the data sets whereas the Margins for some properties reflect heuweltjie typical values, while others are stronger influenced by Matrix characteristics. This is most clearly examplified by pH$_{H2O}$-results as is shown in Fig. 4.9. The pH-niveau of all three D3-units is high and comparable with the Heuweltjie-units of the other D2-areas, while the Matrix-unit assumes a transitional position between Centre and Margin.

The heuweltjie on the Western Slope (WS) represents a third type. The underlying slope inclination represented by the respective Matrix-unit reaches approx. 23% and is roughly double inclined than the other three D2-units (in comparison: Lower Eastern Slope (ES): 11%, Accumulation Zone (AC): 12%. See also Tab. 4.17). The heuweltjies occurring here are strongly transformed by downward sedimentation and erosion so that boundaries between Centre, Margin and Matrix are obliterated in downslope direction and height differences between Heuweltjies and Matrix were levelled over time. It has to be considered here that Matrix and Heuweltjie study sites were not established as a transect so that run-on/ run-off processes are not directly deducable in this example. The special genesis of this heuweltjie-type is reflected in the data set: differences between the three D3-areas are far less pronounced compared to Lower Eastern Slope (ES) and Accumulation Zone (AC) examples. This is shown for instance for the parameters Al$_t$, Na$_t$ and N$_t$ (Fig. A.2 to A.14). When regarding the total data set, it can be stated that total element contents

substrate	clay	silt	sand
mean AC-HC	8.6	18.4	73.0
mean AC-HM	6.7	14.2	79.1
mean AC-MA	5.0	14.1	80.9
mean WS-HC	8.1	24.7	58.9
mean WS-HM	8.2	26.1	65.7
mean WS-MA	8.7	26.5	64.9
mean ES-HC	10.3	33.9	55.8
mean ES-HM	8.6	31.7	59.7
mean ES-MA	4.3	23.7	71.9
mean ES-QF	10.7	23.4	66.0
mean total MP	7.9	21.9	69.3

Tab. 4.4: Clay, silt and sand contents of the D3-units in slope positions.

are generally well grouped on the D3-scale. Organically driven parameters often deviate strongly, especially C_{org} and N_t when samples of dead shrub or canopy locations were involved. With regard to these parameters a masking effect due to lower scaled units on the D3-scale is possible, especially when data sets with varying D4-composition are compared (Fig. 4.10, see also Chapter 2.4.6). On the other hand, C/N-ratios show a clear trend with significantly lower values on Heuweltjie-units (either Centre or Margin) compared to Matrix-units with one exception: on the Lower Eastern Slope (ES), the Center exhibits the widest values. To which degree D4 alters soil is examined in Chapter 4.4.3 and 4.4.5.

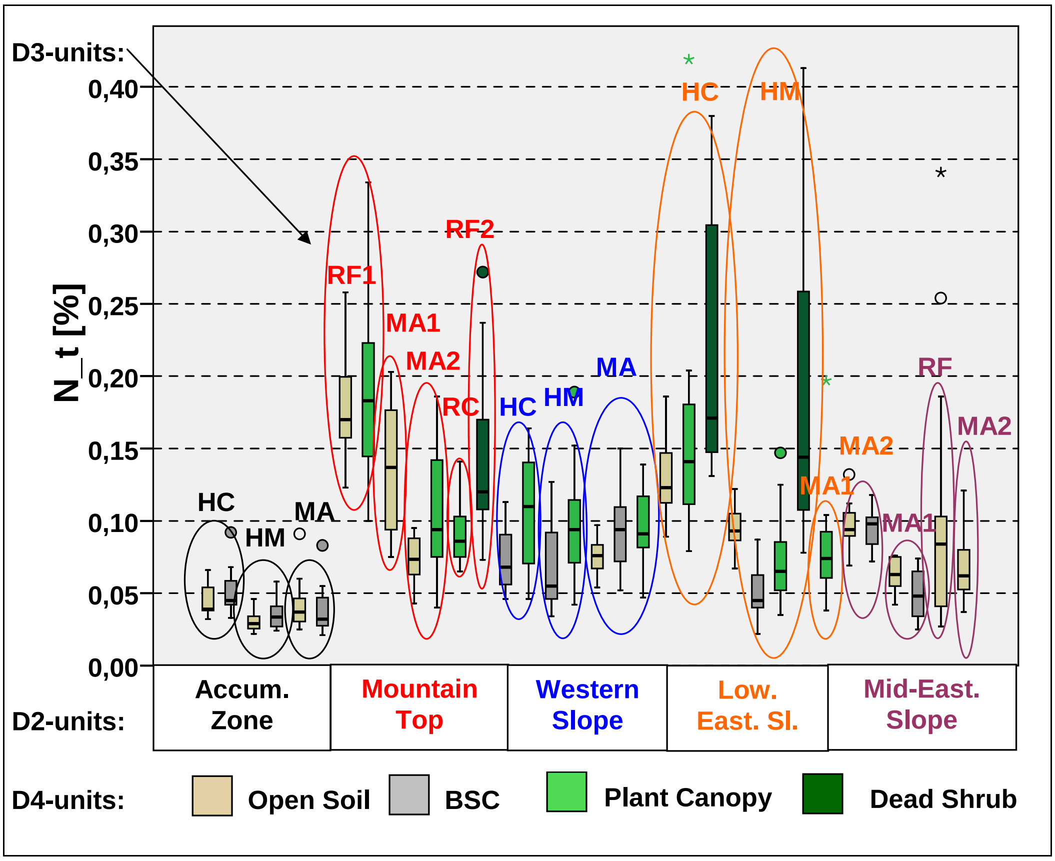

Fig. 4.10: Diagram visualising D4-unit composition of the D3-units sampled in Soebatsfontein: exemplary for the distribution of N_t-values depicted as boxplots. Dead shrub units have a considerable effect on N_t-distribution on D3-scale.

These findings are additionally confirmed by texture data (Tab. 4.4). While the "typical" Lower Eastern Slope (ES) heuweltjie shows increased silt-values that gradually decrease from Centre to Matrix, the blurred Western Slope (WS) heuweltjie did not show strong differences and even rather tends to the opposite trend. The texture analysis of the Accumulation Zone (AC) again revealed increased silt-contents for the Centre, but not for the Margin. This unit more resembled the Matrix in terms of silt and sand, but took an intermediate position in terms of clay content.

D3-Variability on the Rocky Outcrops: the Influence of Rock Fringe-Areas Rocky outcrop areas were analysed on two D2-units: the Mountain Top (MT) and the Mid-Eastern Slope (MS). Expected variability rising units were the Rock Fringe areas since it is assumed that these receive a surplus of nutrients and water. In total, three Rock Fringe units were sampled: one on the Mid-Eastern Slope (MS) study site and two on the Mountain Top (MT). However, these Rock Fringes differ from each other: one Rock Fringe of the Mountain Top (MT-RF1) is located at the foot of approx. 2 m high and steep boulders. The other Rock Fringes are based on the edge of smooth exposed granites that have an angle of approx. 25% on the Mountain Top (MT), and 30% on the Mid-Eastern Slope (MS), respectively. While the former of those consists of a rock pocket surrounded by outcrops, is limited in depth and completely covered with dead and live dwarf shrubs, the Rock Fringe of the Mid-Eastern Slope (MS-RF) merges into a Matrix-unit and is only scarcely vegetated.

Generally, D3-groups of the study sites in focus often show strong variability with only weak grouping (Fig. 4.11, Fig. A.16 to A.19 and Tab. A.3). Exemptions are found for the Rock Fringe below the high boulder on the Mountain Top (MT-RF1). Here, significantly increased values of EC, C_{org}, C/N-ratio, Fe_t and Ti_t and a significant decrease of K_t are found that indicate the expected accumulation of (soluble) organic substances and salts on the one hand, and an increase of clay on this single D3-unit on the other (Tab. 4.5). These effects are not confirmed by the other Rock Fringe data sets.

substrate	clay	silt	sand	coarse sand
mean MT-RF1	10.04	17.2	72.8	20.1
mean MT-MA1	7.99	16.7	75.3	21.0
mean MT-MA2	5.53	15.4	79.1	21.0
mean MT-RC	5.45	14.8	79.8	26.5
mean MT-RF2	7.16	13.8	79.0	26.5
mean MS-MA1	5.86	14.4	79.8	17.5
mean MS-RF	7.46	16.5	76.1	21.6
mean MS-MA2	6.69	17.3	76.0	24.5
mean total MP	7.9	21.9	69.3	14.4

Tab. 4.5: Clay, silt and sand contents of the D3 units in rocky outcrop positions.

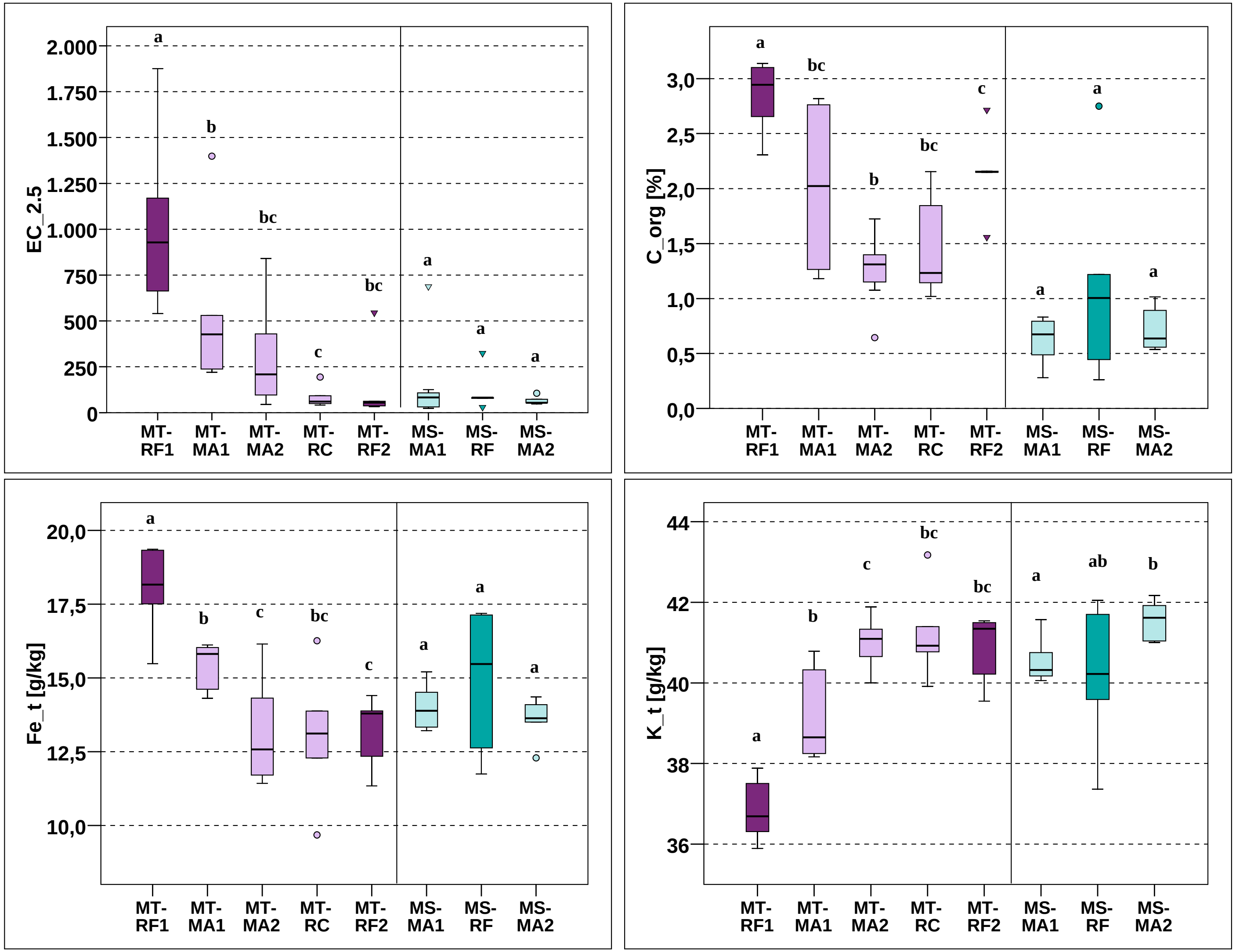

Fig. 4.11: Comparison of Rock Fringe and Matrix-units on D3-scale: Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Mountain Top (MT) in violett colours, Mid-Eastern Slope (MS) in turquoise colours; darker colours designate Rock Fringe-units. Different letters indicate significant differences with $p = 0.05$.

4.4.2.4 Discussion of D3-Units Generating Variability

The results indicate a strong contribution of heuweltjies to total variability of some soil properties, especially pH, Ca_t, P_t, Mn_t, C/N-ratio and Zn_t. Though not significant due to low sample numbers, this is also valid for K_{dl} and P_{dl}, whose values are increased on heuweltjie-sites. These findings are well in accordance with other works: Petersen *et al.* (2003) found that heuweltjies in Soebatsfontein and in the Koeroegabvlakte/Richtersveld were enriched in Ca, Mg, pH_{CaCl2} and silt. Although the published data comprised medians of the whole profile layers, the data is comparable: in the Koeroegapvlakte, pH_{CaCl2} of the centre was increased by 1.2 pH-units compared to the heuweltjie-basis, in Soebatsfontein it was 2.5. In the current data set, pH_{CaCl2} reached increases of 0.8 in the Accumulation Zone (AC), 1.9 in the Western Slope (WS) and 2.7 pH-units on the Lower Eastern Slope (ES). With regard to Ca_t, ranges between heuweltjie centre and base reported by Petersen *et al.* (2003) and between Centre- and Matrix-units of this study deviated more strongly. While Petersen found values of 11 g/kg (base) to 21 g/kg (centre) in the Koeroegapvlakte, and 3 (base) to 21 g/kg (centre) in Soebatsfontein, this study revealed differences of 4 - 13, 5 - 10 and 5 - 30 g/kg with regard to Accumulation Zone (AC), Western Slope (WS) and Lower Eastern Slope (ES), respectively. This, however, is probably due to the exclusive sampling of topsoils.

Hoyer (2004) reports lower C/N-values, increased pH-values, high base saturation and increased silt contents on another heuweltjie in Soebatsfontein. In terms of C/N-ratios, the present study could only partly affirm the statement, which is due to the issue of varying D4-contributions to each D3-data set but also to the above explained different heuweltjie-types. Hoyer (2004) further states that topsoils of 0-15 cm featured low EC-values although in deeper layers EC-values increased to a degree that led to salic and hyposalic attributes in the WRB classification. According to Petersen (2008), who used the recent WRB-classification (IUSS Working Group WRB, 2006), some heuweltjies are even classified as Solonchaks due to their high salt content. This high salinity within the heuweltjie core is the source of the observed high variability in EC-values in some Heuweltjie-units where digging activities of small mammals are pronounced (compare Chapter 4.4.7.3).

Midgley & Musil (1990) found increased macro- and microelement-contents on mound soils compared to off-mound soils. This comprised P, K, Ca, Mg, Cu, Zn, Mn, B, Fe and Al. However, although these results are in accordance with findings of the work at hand, it has to be considered that Midgley & Musil (1990) used another method for determination (Direct Current Plasma Spectrometer following extraction of soil minerals in 1% citric acid soulutions at 80°C). Also, the authors obtained increased gravimetric water contents, silt- and clay values on mound soils.

The analysis of the rocky outcrop soils in Soebatsfontein presented some surprises. It was expected that in Rock Fringe areas an accumulation of salts and organic material would be detectable. This expectation arose from the following thoughts: saxifrageous lichens frequently inhabit the rocks above rock fringes. These were reported to exudate certain lichen acids that play a rock dissoluting and hence soil-forming role (Schatz, 1962; Cooper & Rudolph, 1953). Further, dust particles may stick on the lichen surface and - to a minor degree - on the rocks themselves and are washed off during rain-events (Shure, 1999). Apart from nutrients being released from minerals through rock weathering, salts may additionally be precipitated from seafog on the rocks. After several cycles of wetting and drying, the accumulated salts are finally washed off during rain events. Organic material in soluble form or debris derived from lichens and plants inhabiting rock crevices and cracks, may be translocated downwards into the fringe area. This, however, only applies for the rock fringe zone in the mountain top that was adjacent to very steep boulders.

Interestingly, comparable publications on rock fringes and their soil characteristics in rocky outcrops are scarce so that an evaluation of these result was difficult. Some publications exist for American and Brazilian granite and gneiss outcrops, where rock fringes are termed "soil islands", although vegetational aspects were in focus of these studies and soil properties were only marginally analysed if at all (Meirelles *et al.*, 1999; Collins *et al.*, 1989; Shure, 1999). In Southern African ecosystems several publications deal with the so-called "inselbergs"[3] Both regarded habitats, inselbergs and soil islands, had in common that they were centres of endemism. The difference between them is the scale - while inselbergs are large features in the dimension of a mountain, soil islands are more or less eliptically shaped microhabitats on granite or other outcrops with a mean diameter of maximal 9 m (Burbanck & Platt, 1964). Thus, studies of inselbergs that included soil analysis in rock pockets such as in the work of Burke (2002) focused on slope scale rather than on microscale processes as is done in the current study.

Burbanck & Platt (1964) studied shallow soil islands on smooth flat granite and granite gneiss outcrops in Piedmont. They described these microenvironments as extremely scarce, since they were characterised by high light intensity, lack of moisture due to insufficient rainfall, shallow soils and competition, and rapid evaporation. This extremeness of habitat, however, is seen as the reason for the high degree of endemism which is also true for the rocky outcrop zones of Soebatsfontein. Further, Burbanck & Platt (1964) classified vegetation occurring on rock islands into four plant communities that not only appeared to represent stages in plant succession but also related directly to edaphic conditions. In particular, the classification was in accordance with soil depth: in two centimeter deep soils, a *Diamorpha*-community occurred that represented the lowest successional stage. With increasing soil depth, lichen-annual herb communities and annual-perennial herb communities were described; on the deepest soils reaching a depth of 48 cm, herb-shrub communities occurred as the highest successional stage.

Some results of soil analysis were stated by the authors as well: in this study, shallow soils of 2 cm had an organic content of 3% that rose to 8% in soils of 15 cm in depth. Also, pH rose in the same order from 4.0 to 4.5. Comparing this to the results of the current study, some parallels may be deduced though on a different

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[3] "isolated hills that stand above well-developed plains and appear not unlike an island rising from the sea" (Encyclopedia Britannica). Examples for inselbergs are Ayers Rock in Australia, the Sugar Loaf Mountain in Rio de Janeiro or the Namibian Mountain Spitzkoppe.

parameter level when assuming that the Rock Fringe-unit MT-RF1 is deepest with approx. 25 centimeter, followed by MT-RF2 with approx. 15 centimeter and MS-RF1 with approx. 10 cm. This applies for pH_{H2O} and - more obviously - for pH_{CaCl2}, but also for N_t. For C_{org} this effect is less clear. However, it has to be considered, that on MT-RF1 two D4-units occurred that were both involved in the analysis: Open Soil and Plant Canopy, of which the latter was characterised by approx. 2 m high, woody shrubs of the species *Stoeberia utilis*. In the MT-RF2-unit, a mixture of dead and live dwarf shrubs dominated the D4-scale which left no open soil in between. Also, MT-RF2 was more shaped like a pocket so that run-on probably exceeded runoff, than MT-RF1, which was stronger sloped so that downward translocation of plant litter was likely. These findings applied also to further organically related parameters such as C/N-ratio and S_t, K_{dl}, P_{dl} but astonishingly not to NO_{3we} whose values were neglectible on the Mountain Top area but reached highest values in MS-RF, exceeding the Matrix-units. One reason may be the low plant coverage in this Rock Fringe, and therefore the lack of consuments in contrast to other investigated Rock Fringes.

Shure (1999) describes the genesis of soil islands as the combined effect of physical weathering of the granite due to the impact of winter cold and summer heat which lead to the formation of exfoliation depressions that are gradually filled with weathering material. Thus, typically these very young soils consist of sandy-gravelly mineral substrates. In addition, lichens may loosen granit particles that are in turn redistributed by wind and water and trapped by plants. This formation hypothesis corresponds to findings on texture (Tab. 4.5): when comparing the texture data of the three Rock Fringes with texture data of total texture analyses of Soebatsfontein, all Rock Fringes show lower silt but higher coarse sand contents. MT-RC and MT-RF2 feature the highest coarse sand values which exceed the mean of the total data set nearly twofold, followed by the MS-RF with a 7% and MT-RF1 with a 5.5% increase. However, in some cases clay was found to be increased in Rock Fringe soil as well. In MT-RF1, clay content was approx. 3% higher compared to the mean clay content calculated for the whole data set. Conclusively, two sources of material fill up the Rock Fringes: on the one hand coarse particles derived from physical weathering, on the other clay particles derived from biochemical weathering of rock inhabiting lichens and plants.

4.4.3 Variability on D4-Scale: Mutual Dependencies between Biological Soil Crusts and Soil Properties

For the analysis of mutual dependencies between open soil and biological soil crusting, six pairs of data sets comparing Open Soil (O)/ BSC encrusted soil (B) on the D4-scale were available with each data pair being located at a different site with regard to the combination of superior D3 and D2-units, respectively. For parameters that were fully analysed, the data set comprised n = 5 values per D4-unit and layers of each pair, given that each D4-unit was sampled with five miniprofiles. For other parameters, such as waterextractable anions and cations, n = 2 values were available for statistical analysis, since here analyses were conducted for the two out of five miniprofile-samples where EC was lowest and highest, respectively, to cover the whole range of water extractable anions and cations.

4.4.3.1 Significance Tests within the complete Data Set

A comparison of BSC encrusted and Open Soils was conducted using the data set of six BSC and corresponding Open Soil pairs[4]. Since the data did not meet the requirements of parametric tests, U tests were conducted to screen the data set on significant differences between the two D4-units in question. Further, the different D4 pairs had to be made comparable by eliminating the underlying different base soil properties that were due to the kind of D3 and D2 sites where the soil samples were taken (see Chapter 2.4.5).

In this first approach, the layer 0-1 cm was particularly interesting since BSCs only inhabit the upper millimetres of soil. The analysis revealed in at least two layers significantly increased values of pH_{H2O}, pH_{CaCl}, Al_t, K_t and Mn_t on BSC-sites compared to Open Soil sites (see Tab. 4.6). In addition, the differences in pH_{H2O}, pH_{CaCl} and Al_t increase with depth. Ti_t and Fe_t are significantly increased in the first centimetre but show only slightly increased mean values in deeper layers. On BSC-sites within the first centimetre, Zn_t is strongly and significantly increased, in the samples taken below that layer, however, means are lower on BSC sites compared to Open Soil sites, though not significant. Interestingly, the two pH-measurements differ strikingly in the first layer, where pH_{H2O} shows a significant increase due to BSC influence, while pH_{CaCl} does not show differences between the two D4-units.

Strong interactions between BSCs and soil properties with decreased values compared to non-crusted sites were observed for C/N-ratio, S_t, and NO_{3we}. Apart from these most obvious differences, further interactions were detected applying the U test: salt-affected parameters are decreased on BSC-sites. This was tested significant for

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[4] a seventh data pair was sampled on the Mid-Eastern Slope (MS) site. However, only two miniprofiles were sampled on Open Soil patches, since nearly the whole area was encrusted with BSC, even when examining the area around the small scale study site. ANOVA analysis required balanced sampling schemes with equal sample numbers. Therefore, the Mid-Eastern Slope data was excluded from the analysis at this point

	0-1 cm		1-5 cm		5-10 cm	
Parameters	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH_{H2O}	60	0.28 * ± 0.35	60	0.37 * ± 0.50	60	0.45 * ± 0.57
pH_{CaCl}	60	0.01 ± 0.25	60	0.14 * ± 0.27	60	0.23 * ± 0.33
$EC_{2.5}$ [µS/cm]	60	-309 ± 609	60	-360 * ± 652	60	-250 ± 592
EC_5 [µS/cm]	60	-184 ± 354	60	-230 * ± 393	60	-165 ± 346
C_{org} [%]	60	-0.03 ± 0.34	59	-0.17 * ± 0.25	60	-0.14 ± 0.28
N_t [%]	60	0.004 ± 0.028	59	-0.009 ±0.020	60	-0.008 ± 0.024
C/N-ratio	60	-1.15 * ± 0.94	59	-1.10 * ± 1.30	60	-1.17 * ± 1.77
P_{dl} [g/kg]	23	-0.04 ± 0.07		-		-
K_{dl} [g/kg]	23	0.04 ± 0.10		-		-
S_t [g/kg]	60	-0.05 * ± 0.07	60	-0.11 * ± 0.13	60	-0.08 * ± 0.16
Al_t [%]	60	0.18 * ± 0.38	60	0.19 * ± 0.35	60	0.24 ± 0.44
K_t [g/kg]	60	0.47 ± 1.74	60	1.18 * ± 1.77	60	1.05 * ± 2.10
P_t [g/kg]	60	-0.04 ± 0.08	60	-0.03 ± 0.08	60	-0.03 ± 0.08
Ti_t [g/kg]	60	0.90 * ± 4.21	60	0.03 ± 0.18	60	0.07 ± 0.23
Fe_t [g/kg]	60	0.70 * ± 2.44	60	0.02 ± 1.52	60	0.53 ± 2.21
Mn_t [mg/kg]	60	1.039 * ± 5.47	60	0.010 ± 0.13	60	0.007 * ± 0.18
Zn_t [mg/kg]	60	3.55 * ± 7.12	60	-0.47 ± 4.25	60	-0.17 ± 6.98
Cl_{we} [mg/l]	24	-476 ± 786	24	-388 ± 748	24	-319 ± 539
Br_{we} [mg/l]	24	-0.66 ± 0.99	24	-0.68 * ± 0.97	24	-0.65 ± 0.97
NO_{3we} [mg/l]	24	-13 * ± 15	24	-12 * ± 13	24	-11 * ± 11
SO_{4we} [mg/l]	24	-39 * ± 58	24	-134 ± 201	24	-59 ± 282
Ca_{we} [mg/l]	24	-59 * ± 91	24	-76 ± 110	24	-27 ± 89
Mg_{we} [mg/l]	24	-97 ± 173	24	-132 ± 211	23	-33 ± 74
Na_{we} [mg/l]	24	-111 ± 187	24	-140 ± 211	24	-116 ± 219
K_{we} [mg/l]	24	-6 ± 18	24	-2 ± 15	24	1 ± 15
$Anions_{we}$ [mg/l]	24	-14 ± 24	24	-14 ± 25	24	-10 ± 20
$Cations_{we}$ [mg/l]	24	-16 ± 27	24	-21 ± 32	24	-8 ± 16

Tab. 4.6: Comparison of Open Soil (O) and BSC encrusted soil (B) for the three individual layers. Presented is the difference of the mean with regard to BSC samples compared to Open Soil after standardisation of the data set (explanation see Chapter 2.4.5). Negative values imply lower contents on BSC-sites compared to Open Soil.

$EC_{2.5}$, EC_5 in layer 1-5, and for $SO4_{we}$ and Ca_{we} in the first centimetre. The trend is also visible for all other layers and further water extractable cations and anions such as Cl_{we}, Br_{we} and Mg_{we}, K_{we} (with the exeption of the last layer), Na_{we} and total cations$_{we}$ and anions$_{we}$. The same was valid for C_{org}. Most strikingly, C_{org} values do not differ within the first layer, the actual growth zone of BSC, and moreover, decrease significantly with depth. P_{dl} showed decreased levels in samples of the first centimetre topsoil with a significance of $p < 0.1$ and K_{dl} does not show clear trends.

Texture analysis was conducted after combining the five parallel samples of one layer within the same D4-unit to one composite sample. Differences between BSC and Open Soil patches were tested with Mann-Whitney U tests for the separate layers. However, there are again different preconditions because of varying parent materials with a different D3 and D2-influence that had to be eliminated first by standardisation as described above. This way, $n = 6$ BSC-samples could be compared to $n = 6$ open soil samples (Tab. 4.7).

When regarding the three sample layers individually, a tendency of the topsoil centimetre to be connected with increased fine particle contents becomes clearly visible. This comprises in detail fine, coarse and total silt. By contrast, total sand is significantly decreased on BSC sites. Moreover, regarding deeper layers, further differences on the 0.05 level are detectable; in 1-5 cm, BSC sites tend to have more silt, finest fine sand and fine sand and less coarse sand than Open Soil sites. And in 5-10 cm samples, BSC-sites are connected with significantly less coarse and total silt, but increased contents of finest fine sand.

Fraction [%]	N	0-1 cm	1-5 cm	5-10 cm
Clay	12	-1.09 ± 3.34	-0.48 ± 1.98	-0.11 ± 1.85
Silt	12	5.07 * ± 3.32	0.70 * ± 2.07	-1.88 * ± 2.51
fSi	12	0.80 * ± 0.61	-0.36 ± 0.94	-0.54 ± 0.94
mSi	12	0.57 ± 1.01	0.30 ± 0.95	-0.41 ± 1.02
cSi	12	3.69 * ± 2.85	0.75 ± 1.46	-0.93 * ± 1.25
Sand	12	-3.98 * ± 2.45	-0.20 ± 2.72	2.02 ± 3.76
fS	12	-1.20 ± 3.93	0.98 * ± 0.99	1.11 ± 1.60
ffS	12	-1.01 ± 3.66	1.05 * ± 0.25	0.73 * ± 1.36
cfS	12	-0.19 ± 0.66	-0.07 ± 0.98	0.38 ± 1.01
mS	12	-2.40 ± 3.96	-0.37 ± 1.64	0.50 ± 1.63
cS	12	-0.38 ± 2.27	-0.81 * ± 1.29	0.40 ± 1.16

Tab. 4.7: Comparison of particle size distribution of Open Soil (O) and BSC encrusted soil (B) within three individual layers: difference of mean of BSC samples compared to Open Soil after standardisation of the data set. Means are presented with standard deviations.

4.4.3.2 Significance tests within Individual Sites

The question remained, whether the detected differences are generally valid across all sites tested. Therefore, for the parameters that were tested as significant in the whole data set, U tests were also conducted for single sites. Since here each data pair was tested separately, it was not necessary to use the standardised data set and original data was used. A selection of the results is presented in Tab. 4.8.

This analysis points out that the determined trends are pronounced very differently on the test sites. For pH$_{H2O}$ for instance, the difference that was tested within the whole data set could only be confirmed on two out of six D3-units on a $p < 0.05$ significance level, which is probably due to the low number of $n = 5$ for each layer per site. This sample number is not sufficient to determine significant differences in the strongly varying data set although the trend is consistent when depicting it graphically (compare Fig. 2.2). In general, differences of the mean values between Open Soil and BSC encrusted samples range between 0 and 1.2 pH-units between the six sites. On all sites and all layers, pH was nearly always increased on BSC encrusted sites, seldomly equal but never lower. It has to be noted that the effect of BSCs on pH-increase is strongest on Western Slope Matrix site (WS-MA) where pH is generally lowest. For EC$_{2.5}$, however, the site-specific differences deviate strongly: the six sites showed heterogenous tendencies with regard to data distribution between the two D4-groups and within layers: One site, the Heuweltjie-Center on the Accumulation Zone (AC-HC), showed increased EC values below BSC in all layers and on both, Open Soil and BSC patches with depths. All other sites showed decreased values below BSC. On the Heuweltjie-Margin of the Accumulation Zone (AC-HM), EC-values decreased on Open Soil sites but increased on BSC sites with depths. On the Matrix site within the Accumulation Zone (AC-MA), the EC level was generally low with maximal means of 64 μS/cm; while on Open Soil the EC-level stayed the same with depth, it decreased on the BSC-unit. This was very similar below BSC on the Western Slope Matrix site (WS-MA), although on the corresponding Open soil unit, EC was manifold increased but also declined in deeper layers. On the last two sites, the Matrix 2 and the Heuweltjie Margin of the Lower Eastern Slope (ES-MA2 and ES-HM), Open soil and BSC-units showed higher EC-values with depths, but BSC showed lower values in comparison with Open Soil.

C$_{org}$ and N$_t$ showed strong inconsistencies between the sites. On one site (Heuweltjie-Center on Accumulation Zone, AC-HC), all C$_{org}$-values are increased on BSCs, in the last layer even significantly. The same is valid vor N$_t$-values, though only in weak trends. The contrary is true for another site, the Heuweltjie-Margin on the Lower Eastern Slope (ES-HM), where all layers show significantly less C$_{org}$ and N$_t$ below BSCs compared to Open Soil. On two further sites (Matrix on Accumulazion Zone (AC-MA) and Matrix 2 on Lower Eastern Slope (ES-MA2)), C$_{org}$ was in nearly all cases lower at BSCs and approximately with regard to N$_t$. The Heuweltjie-Margin of the Accumulation Zone (AC-HM) and the Matrix of the Western Slope (WS-MA) showed increased values of C$_{org}$ and N$_t$ in the first layer, which was significant for WS-MA; below this layer, C$_{org}$-values decreased and N$_t$-values were about the same.

Other parameters do not show such strong variation between the sites: C/N-ratios and S_t show consistent trends and confirm the results of the previous test that combined all sites to one standardised data set. Nevertheless, exemptions from the rule are common: this is especially true for the Heuweltjie-Center of the Accumulation Zone (AC-HC), which oftenly shows inverse trends compared to the other sampling sites (see Tab. 4.8, $EC_{2.5}$, C/N-ratio, S_t).

		pH_{H2O}		$EC_{2.5}$ [µS/cm]		S_t [g/kg]	
Site	**Layer**	**O**	**B**	**O**	**B**	**O**	**B**
AC-HC	**0-1**	8.6 ± 0.27	8.6 ± 0.19	114 ± 18	154 ± 39	0.25 ± 0.05	0.26 ± 0.06
	1-5	9.0 ± 0.53	9.3 ± 0.35	118 ± 25	142 ± 42	0.21 ± 0.04	0.23 ± 0.03
	5-10	9.2 ± 0.51	9.4 ± 0.23	161 ± 60	172 ± 60	0.19 ± 0.02	0.22 ± 0.05
AC-HM	**0-1**	7.8 ± 0.48	7.9 ± 0.62	523 ± 928	369 ± 415	0.21 ± 0.04	0.19 ± 0.06
	1-5	7.9 ± 0.62	8.5 ± 0.62	504 ± 691	280 ± 397	0.25 ± 0.13	0.17 ± 0.05
	5-10	7.7 ± 0.89	8.3 ± 0.66	486 ± 662	416 ± 610	0.26 ± 0.12	0.22 ± 0.13
AC-MA	**0-1**	8.1 ± 0.40	8.3 ± 0.21	63 ± 31	64 ± 40	0.22 ± 0.05	0.19 ± 0.08
	1-5	8.7 ± 0.51	8.7 ± 0.11	50 ± 26	34 ± 20	0.19 ± 0.03	0.14 ± 0.07
	5-10	8.9 ± 0.44	8.9 ± 0.23	64 ± 39	48 ± 21	**0.19 ± 0.01**	**0.13* ± 0.04**
WS-MA	**0-1**	**6.0 ± 0.33**	**6.4* ± 0.23**	**1656 ± 1009**	**61* ± 14**	**0.32 ± 0.04**	**0.23* ± 0.04**
	1-5	**5.5 ± 0.34**	**6.3* ± 0.44**	**1778 ± 852**	**35* ± 14**	**0.56 ± 0.19**	**0.20* ± 0.03**
	5-10	**5.2 ± 0.52**	**6.4* ± 0.55**	**1452 ± 572**	**40* ± 12**	**0.50 ± 0.19**	**0.19* ± 0.05**
ES-MA2	**0-1**	6.4 ± 0.43	6.8 ± 0.26	131 ± 144	84 ± 60	0.24 ± 0.04	0.23 ± 0.03
	1-5	6.2 ± 0.79	6.6 ± 0.65	208 ± 320	105 ± 72	0.30 ± 0.10	0.25 ± 0.05
	5-10	5.6 ± 0.68	5.8 ± 0.63	263 ± 358	297 ± 356	0.31 ± 0.11	0.37 ± 0.23
ES-HM	**0-1**	**8.7 ± 0.15**	**9.2* ± 0.17**	**185 ± 34**	**91* ± 37**	**0.35 ± 0.05**	**0.19* ± 0.02**
	1-5	**9.4 ± 0.36**	**9.6* ± 0.24**	214 ± 65	113 ± 32	**0.31 ± 0.04**	**0.15* ± 0.01**
	5-10	**9.3 ± 0.25**	**9.8* ± 0.17**	255 ± 144	206 ± 70	**0.33 ± 0.07**	**0.15* ± 0.01**

		C_{org} [%]		N_t [%]		C/N-ratio	
Site	**Layer**	**O**	**B**	**O**	**B**	**O**	**B**
AC-HC	**0-1**	0.502 ± 0.074	0.546 ± 0.113	0.059 ± 0.007	0.068 ± 0.014	8.4 ± 0.4	8.0 ± 0.7
	1-5	0.327 ± 0.037	0.369 ± 0.051	0.040 ± 0.002	0.044 ± 0.004	8.2 ± 0.6	8.4 ± 0.5
	5-10	**0.283 ± 0.033**	**0.342* ± 0.042**	0.036 ± 0.003	0.040 ± 0.005	7.9 ± 0.5	8.5 ± 0.4
AC-HM	**0-1**	0.324 ± 0.076	0.402 ± 0.110	0.035 ± 0.009	0.046 ± 0.011	9.2 ± 0.5	8.8 ± 0.8
	1-5	0.314 ± 0.113	0.294 ± 0.069	0.029 ± 0.005	0.031 ± 0.007	10.5 ± 3.1	9.4 ± 1.4
	5-10	0.310 ± 0.123	0.269 ± 0.043	0.029 ± 0.009	0.029 ± 0.007	10.7 ± 2	9.3 ± 1.6
AC-MA	**0-1**	0.559 ± 0.274	0.493 ± 0.179	0.056 ± 0.021	0.055 ± 0.016	9.7 ± 1.0	8.8 ± 0.6
	1-5	0.333 ± 0.141	0.283 ± 0.095	0.037 ± 0.013	0.032 ± 0.009	8.8 ± 0.7	8.7 ± 0.6
	5-10	0.346 ± 0.135	0.247 ± 0.048	0.033 ± 0.005	0.026 ± 0.004	10.3 ± 2.1	9.4 ± 0.7
WS-MA	**0-1**	**1.114 ± 0.162**	**1.550* ± 0.328**	**0.077 ± 0.008**	**0.122* ± 0.019**	**14.4 ± 0.7**	**12.7* ± 0.9**
	1-5	1.445 ± 0.301	1.227 ± 0.281	0.084 ± 0.015	0.086 ± 0.019	**17.1 ± 0.8**	**14.3* ± 0.7**
	5-10	1.207 ± 0.144	1.056 ± 0.326	0.067 ± 0.010	0.071 ± 0.020	**18.0 ± 0.7**	**14.9* ± 1.7**
ES-MA2	**0-1**	1.330 ± 0.288	1.204 ± 0.145	0.108 ± 0.016	0.108 ± 0.010	12.3 ± 0.9	11.1 ± 0.6
	1-5	1.433 ± 0.194	1.236 ± 0.235	0.100 ± 0.006	0.091 ± 0.013	14.3 ± 1.2	13.6 ± 0.8
	5-10	1.359 ± 0.187	1.401 ± 0.144	0.081 ± 0.009	0.084 ± 0.010	16.8 ± 0.9	16.7 ± 2.0
ES-HM	**0-1**	**1.120 ± 0.097**	**0.570* ± 0.114**	**0.110 ± 0.009**	**0.072* ± 0.012**	**10.2 ± 0.1**	**7.8* ± 0.3**
	1-5	**0.898 ± 0.071**	**0.347* ± 0.077**	**0.086 ± 0.005**	**0.042* ± 0.007**	**10.4 ± 0.4**	**8.2* ± 0.6**
	5-10	**0.952 ± 0.210**	**0.301* ± 0.093**	**0.091 ± 0.016**	**0.036* ± 0.009**	**10.3 ± 0.8**	**8.2* ± 0.9**

Tab. 4.8: Comparison of Open Soil (O) and BSC encrusted soil (B) on the individual sites. Data are presented of selected parameters and for the individual layers. Superscripts * indicate significant difference on BSC compared to Open Soil. Means are presented with standard deviations.

Tab. 4.9 shows the site resolved contents of the parameter NO_{3we} in addition to the contents of N_t. While the results of N_t are largely heterogenous for the different sites and layers, NO_{3we} shows a substantially clear trend: except for the Heuweltjie-Center of the Accumulation Zone (AC-HC) again, NO_{3we}-contents are lower in all layers of BSCs compared to Open Soil samples. It has to be noted that significance tests were omitted for this data set since for each layer a sample number of only n = 2 was available.

Conclusively, significant differences when comparing the data of all six sites are not in all cases verified when regarding single pairs for each D3-unit. In most cases, the differences between Open Soil and BSC encrusted soil samples remain low but confirm the general trend. In few cases, strongly depending on the combination of D3 and D2-site regarded, the results for the two D4-units differ strongly with regard to some soil properties. This is especially true for the Matrix-unit on the Western Slope (WS-MA), which shows extreme differences in most parameters and in all layers (esp. $EC_{2.5}$).

		NO_{3we} [mg/l]	
Site	**Layer**	**O**	**B**
AC-HC	**0-1**	2.7 ± 0.2	1.3 ± 1.8
	1-5	1.3 ± 1.5	3.4 ± 1.6
	5-10	0.3 ± 0.4	1.2 ± 1.7
AC-HM	**0-1**	18.5 ± 3.9	1.0 ± 1.3
	1-5	7.2 ± 9.8	0.1 ± 0.1
	5-10	7.2 ± 10.0	0.1 ± 0.1
AC-MA	**0-1**	9.8 ± 4.5	2.6 ± 2.8
	1-5	3.7 ± 4.5	0 ± 0
	5-10	3.5 ± 5.0	0.1 ± 0.1
WS-MA	**0-1**	48.2 ± 2.5	5.7 ± 1.3
	1-5	42.2 ± 3.4	4.5 ± 3.6
	5-10	27.8 ± 2.1	2.9 ± 0.1
ES-MA2	**0-1**	9.3 ± 5.2	2.0 ± 0.8
	1-5	13.4 ± 10.7	1.9 ± 0.3
	5-10	6.1 ± 7.1	1.2 ± 1.7
ES-HM	**0-1**	4.6 ± 3.4	0.7 ± 1.0
	1-5	12.8 ± 4.3	0.8 ± 1.0
	5-10	30.1 ± 42.6	3.3 ± 0.6

Tab. 4.9: Comparison of Open Soil (O) and BSC encrusted soil (B) on the individual sites - continued.

4.4.3.3 Threefactorial Analysis of Variance (ANOVA) including all Sites

In a next step, the question of interest was to which degree the significant differences in soil properties between BSC and non-crusted sites were contributing to overall variability of the data base in focus. For this purpose, a three factorial ANOVA was conducted that included the factors "D4" with the levels "Biological Soil Crust" and "Open Soil", the factor "Site", with levels referring to the six locations where both, BSC affected soils and Open Soils were sampled, and a factor "Layers" with the levels 0-1, 1-5 and 5-10 cm sampling depth. The factor "Site" is a combination of the D2- and D3-unit in question, since a splitting in D2 and D3 was not possible following the ANOVA requirement of a data matrix where all factors are combinable.

Tab. 4.10 clearly shows that variability is rather controlled by the Site-factor than small scale patchiness on the D4-scale. While sites explain in half of the parameters far more than 50% of overall variability with highest contributions reaching up to 93%, main effects of D4 seldomly exceed 10%. Exemptions are NO_{3we} with top scores of

22%, Br_{we} with 13%, and S_t with 12% contribution to overall variability. On the other hand, the interaction scores of the factors D4 and Site reveal a stronger site-specific influence of D4. In other words, on some sites D4 contributes strongly to variability, in others less.

In general, the effect of sampling depths expressed as factor "Layer" and the interactions between the factors Layer and D4 remain low. However, the role of the Layer is stronger expressed in interactions with Site and, albeit to a lesser degree, with D4 and Site. Thus, the Layer-factor does not have to be disregarded, but is strongly variable depending on the presence of BSC and the site character. By regarding the error variances, that are a measure of non-explained or residual variance, it can be stated that for most parameters the factors "Site", "D4" and "Layer" explain more than 50% of the variability. Highest scores for explained variability with more than 90% are found for the parameters Mn_t, Zn_t, Mg_t, pH_{H2O}, C_{org}, Ti_t and C/N ratio.

Parameter	D4	Site	Layer	Site * D4	Site * Layer	D4 * Layer	Site * D4 * Layer	Residual-variance
NO_{3we}	**22**	27	0	19	**7**	0	**4**	20
Br_{we}	**13**	25	**1**	19	3	0	3	36
S_t	**12**	18	0	17	**6**	**1**	**4**	**41**
Ca_{we}	**10**	21	1	**27**	**4**	**1**	1	34
$Cations_{we}$	**9**	20	0	**21**	**5**	**1**	3	**40**
Na_{we}	**9**	25	**2**	18	2	0	1	**43**
Cl_{we}	**9**	27	0	**23**	2	0	1	37
$Anions_{we}$	**9**	27	0	**24**	2	0	1	36
EC_5	**9**	23	0	**28**	1	0	0	39
$EC_{2.5}$	8	24	0	**28**	1	0	0	38
P_{dl}	7	62	0	19	0	0	0	12
HCO_{3we}	6	5	**4**	9	**11**	**7**	**9**	**48**
Pb_t	5	32	0	7	2	0	1	**52**
Mg_{we}	5	18	0	10	2	**3**	**9**	**48**
SO_{4we}	5	19	**5**	16	**9**	**1**	**5**	**40**
P_t	4	61	1	**22**	1	0	0	11
Al_t	3	62	1	4	1	0	1	28
C/N ratio	3	74	**5**	2	**6**	0	0	10
Sr_t	3	64	0	15	1	0	0	16
K_t	3	65	0	6	1	0	1	23
pH_{H2O}	2	**85**	1	1	3	0	0	8
C_{org}	1	**78**	**2**	5	2	0	2	10
K_{we}	1	14	**7**	11	**7**	**1**	**7**	**52**
Ti_t	1	**84**	0	2	2	0	1	10
pH_{CaCl2}	0	**89**	1	0	3	0	0	7
Fe_t	0	**81**	0	2	2	0	1	13
Mn_t	0	**93**	0	2	0	0	0	5
Zn_t	0	**93**	0	0	1	0	0	6

Tab. 4.10: Variance components (%) of the factors Site, D4-unit, Layer, combinations of these and non-explained residual variance. Boxes highlighted grey represent the highest variance components (the upper quantile) within a factor across all parameters.

4.4.3.4 Twofactorial Analysis of Variance (ANOVA) for Individual Sites

After this overview on variance components taking all site data into account, it was tested whether the observed trends are the same for all sites. Therefore, twofactorial ANOVAs were conducted for each site and their variance components compared (see Fig. 4.12).

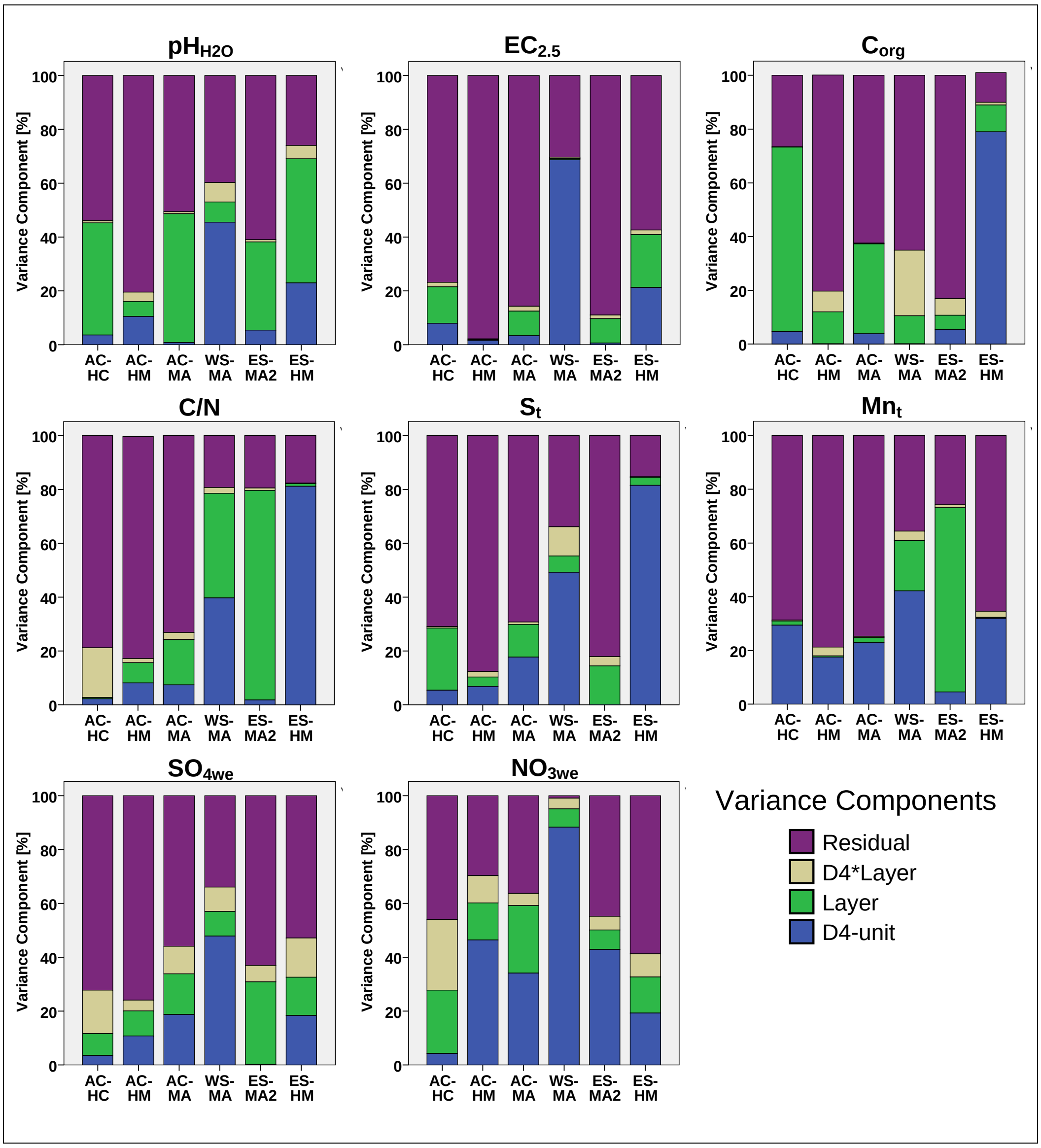

Fig. 4.12: Variance components of the factors D4-unit, Layer, combinations of these and non-explained residual variance determined by a two-way ANOVA for the separate sites.

Generally it holds true for most parameters that residual variances incorporate the largest variance component on the different sites and interactions between the factors D4 and Layer are of rather low importance. However, exceptions to this trend are not uncommon; the Heuweltjie-Center of the Accumulation Zone (AC-HC), for instance, exerts a stronger contribution to overall variance in interactions of D4 and Layer in terms of C/N-ratio and NO_{3we} compared to the other sites and on the Western Slope Matrix site (WS-MA), the factor combination of D4 and Layer contributes with regard to C_{org} 25% to overall variability. Also, regarding C/N-ratio, residual variances of the sites Western Slope Matrix (WS-MA), Lower Eastern Slope Matrix 2 (ES-MA2) and Heuweltjie-Margin on Lower Eastern Slope (ES-HM) are comparably low in favour of a high variance component of the factor D4-unit (ES-HM), Layer (ES-MA2) and both (WS-MA).

When regarding the variance components of D4 and Layer exclusively, it often occurs that the various sites respond very differently: for the parameter C_{org} and S_t for instance, variances that are explained by D4-units range between around zero (Matrix 2 of Lower Eastern Slope, ES-MA2) and 80% (Heuweltjie-Margin on Lower Eastern Slope, ES-HM). ES-HM also contributes highly to the variability of C_{org} on the D4-scale. Parameters with a higher variance component due to D4 are Mn_t, NO_{3we}, C/N-ratio (although varying strongly from site to site), pH_{H2O} and - in cases - S_t and SO_{4we}. Parameters with the factor "Layer" contributing more strongly to overall variability, are N_t, C/N-ratio, pH_{H2O}, SO_{4we} and NO_{3we}.

Three sites show particularly striking trends in their variability:

- Matrix on Western Slope (WS-MA) with regard to $EC_{2.5}$, C/N-ratio, NO_{3we}
- Heuweltjie-Margin on Lower Eastern Slope (ES-HM) with regard to C_{org}, C/N-ratio and S_t
- Matrix 2 on Lower Eastern Slope (ES-MA2) with regard to C/N-ratio and Mn_t

4.4.4 Discussion of Mutual Dependencies between Biological Soil Crusts and Soil Properties

Several publications exist on the influence of BSCs on soils and their potential role within landscapes. Most of them focus on the effect of BSCs on N- and C-input, since some BSC inhabiting cyanobacteria are known to have N-fixing abilities and it is widely accepted that this plays a major role within the often N-depleted arid and semi-arid ecosystems. N-fixation rates of cyanobacterial BSCs have been quoted by West (1990) to range between 2 - 41 kg N ha^{-1} $year^{-1}$. Belnap (2002) calculated an input of 1.4 to 9 kg N ha^{-1} $year^{-1}$ for cyanobacteria dominated soil crusts in Utah, USA. A study in Southern Africa conducted by Aranibar *et al.* (2003) led to estimations of 8 to 44 kg N ha^{-1} $year^{-1}$. Further, a significant input of C due to biocrusts was found by several authors. Reviewing the varying estimations, Evans & Lange (2001) present a range of C-input into the ecosystem by cyanobacteria-dominated crusts of 4 - 23 g C

ha^{-1} $year^{-1}$. Apart from the elemental input, the presence of BSCs is attributed with low C/N-ratios which increase decomposition rates and make nutrients more readily available (Belnap *et al.*, 2001c).

When regarding the results of the present study, the above-described increased values of N and C could not be confirmed on small scale patterns of BSC and non-crusted sites in Soebatsfontein. N_t did not show any significant differences between BSC sites and Open Soil sites in the combined data set of the six sites. When regarding N_t-contents on the single sites, values were in one case higher in all layers, in two cases higher only in the first layer, of which one increase was significant, in one case significantly lower in all layers, and otherwise equal or slightly decreased on BSC-units compared to Open Soil sites. Quite the contrary, NO_{3we} even showed significantly lower contents below BSC in the combined data set. C_{org} was significantly decreased in layers 1-5 and 5-10 cm of the combined data set although no differences could be detected for the top centimetre, the actual growth zone of the photosynthetically active component of the crust. When regarding single sites, the same trends can be observed as for N_t with a mixture of lower, higher or increased values on BSCs, which even vary with depth. On the other hand, the results at hand are in accordance regarding C/N-ratio that was tested significantly lower on BSC patches in all layers and on all sites. However, although this was not expected, similar results had been reported before: in the note of Blank *et al.* (2001), C_{org}-content was lower on two sites with microphytic seedbeds compared to nonmicrophytic seedbeds in Nevada, USA, although this was not statistically significant; Kjeldahl-N content was on the two test sites lower and the same, respectively, compared to the adjacent non-microphytic sites.

K_{dl} showed no significant difference between BSC and non-BSC patches. P_{dl} was even slightly decreased, but only significant on $p < 0.1$ significance level. Findings of other authors are contradictory to these results: according to Harper & Pendleton (1993), especially available P and K were increased by both, cyanobacteria and cyanolichens in soil, as were several other micronutrients such as Ca, Mg, Mn and Na. In further studies, increases of DTPA-extractable Mn, Cu, and Zn (Blank *et al.*, 2001) and Mn and Zn (Bowker *et al.*, 2005) under with BSC were reported. The strongly decreased amounts of total S are also peculiar.

The question emerges, why the expected increases of N, C and other nutrients could not be detected at Soebatsfontein. To analyse this, firstly the role of underlying patchiness of preconditions should be considered. It appeared, that results of individual study sites where samples for comparison of BSC and non-BSC soils were taken varied widely. This may be explained by the range of initial conditions regarding both chemical and texture properties on the sites which is confirmed by the threefactorial ANOVAs. These indicate a strikingly high contribution of site location to overall variability whereas the factor D4 alone, and with that the differentiation into BSC and Open Soil, only accounts for a variability with a maximum of 10%. On the other hand, the also highly variable component in the interaction of D4 and Site factor shows that differences of D4 are expressed quite differently on the varying sites.

Accordingly, it may not be excluded that species composition, coverage and developmental stage of the biocrusts may also differ widely as a consequence of site location. Also, soil units proclaimed as non-BSC sites might not necessarily be totally devoid of such; Pringault & Garcia-Pichel (2004) sampled soil crusts almost exclusively colonised by the filamentous cyanobacterium *Oscillatoria* in a Spanish desert. The authors decribed the crust surfaces as devoid of *Oscillatoria*-filaments and bright white in colour; only after slightly scratching the surface off, a subsurface green layer of the cyanobacteria was revealed. Under wetting, however, *Oscillatoria* started migrating upwards, turning the soil surface into a greenish colour. Conclusively, it might be that on the non-crusted sites of this study, unidentified initial phases of BSC were already existent.

Microtopography probably has a large impact: the sites on which the sample pairs were taken vary strongly with regard to slope and surface roughness as will be discussed in Chapter 4.4.7. BSCs occur on microsites where microtopography is stabilised. This is especially true for the site Western Slope Matrix (WS-MA) where the unit Open Soil occurs along eroded runoff courses and well-developed BSCs on stronger inclined areas inbetween. Though C_{org} and N_t-contents were significantly increased in the first centimetre of BSC-soil, in deeper layers C_{org}-contents were lower compared to Open Soil, and N_t-contents approximately equal but not increased. Data of NO_{3we}, however, showed strongly decreased values on BSCs compared to non-encrusted soil. Strong evidence is given that this is the result of leaching. Further, the N-input by cyanobacterial crusts stated by the above-mentioned authors estimates the input of N into the ecosystem and not into the soil directly as being influenced by BSCs. While the contribution of N into soil by cyanobacteria was assessed by varying experiments in the lab or in-situ measurements of N-production within biocrusted sites, no investigations regarding nutrient patterns related to the spatial occurrence of BSC were conducted. The findings of the present study indicate, that highly soluble nutrients are redistributed in the landscape beyond the boundaries of BSC/ Open Soil patches.

This assumption is in line with the review of nitrogen budgets in BSC-dominated ecosystems by Belnap (2001). She states that in ecosystems N-inputs and -losses occur alike and decoupled in time. Varying studies citet in Belnap (2001) indicate that cyanobacteria and lichens release 5-70% of fixed N into surrounding soils. This extracellular release is greater when environmental conditions such as pH, temperature, light, CO_2 or ionic composition are not optimal, or during wetting after desiccation. Released N is readily taken up by surrounding organisms, including vascular plants, fungi, actinomycetes and bacteria. Some of the liberated N is also reassimilated by the cyanobacteria or lichen.

Different explanations have been suggested for the extracellular release of N. They consider: an unavoidable outward diffusion in low N environments, a membrane deformation with desiccation and rewetting, the toxicity of N compounds or the beneficial attraction of certain organisms. Belnap (2001) further states for BSC encrusted sites in Utah that most N inputs from crusts in this ecosystem occur in autumn, winter and spring, while fixation is minimal in summer, when soil temperatures are high and little moisture is available. Therefore, in the growing season from autumn until summer, nitrogen fixed and released is readily available to plants and microbes.

Belnap (2001) suggests similar scenarios in other deserts that receive most of their rain during cool periods, which matches the conditions in Soebatsfontein. Since all Open Soil and BSC samples regarded in this analysis were taken within five weeks during the rainy season in 2004, the missing differences between Open Soil and BSCs may be interpreted as interactions of N release and uptake by organisms *in sensu* Belnap (2001). It is particularly assumed that plants may play a strong role by extending fine roots actively to areas below BSC patches, the actual location of N-fixation, to readily take up those nutrients where they are delivered continually. This hypothesis is again confirmed by regarding the results of the study site Western Slope Matrix (WS-MA) where BSCs are much more closely associated with plants than with Open Soil and accordingly, watersoluble NO_3 and C_{org} (the latter in all layers exept the first) were strongly decreased below BSC. On the contrary, on the Matrix 2 site of the Lower Eastern Slope (ES-MA2), plants, Open Soil patches and BSC are more equally distributed, since inclination is only small and water courses are less pronounced. Here, the differences between BSC and Open Soil samples with regard to the above-mentioned parameters are less pronounced. Admittently, the equal or unequal distribution of plants, BSC and Open Soil patches is a function of slope and corresponding stability of sites; on areas with low inclination, such as ES-MA2, surface stability is given everywhere. On slopes such as WS-MA, stable sites are particularly found next to plants, in particular in adjacent patches in downhill direction. Therefore, plants determine the establishment and distribution of the BSCs, and not the other way round. Nevertheless, plants most probably benefit from BSCs and cause the unexpected low values of C, N and other nutrients.

pH_{H2O} was strongly increased on the BSC-sites compared to adjacent non-BSC sites with an average increase of 0.4 pH-units on BSC-sites. This is in accordance with the relevant literature: Garcia-Pichel & Belnap (1996), Garcia-Pichel & Belnap (2001) and Büdel (1999) indicate that the photosynthetic activity of BSC may increase pH of the surrounding medium up to 3 pH units. Büdel *et al.* (2004) observed the relation between bioalkalisation by cryptoendolithic cyanobacteria and the weathering of sandstone surfaces in South Africa. In an endolithic model system, they simultaneously measured photosynthetic activity and bioalkalisation of the respective cyanobacteria. Alkalinisation was strongly correlated with photosynthetical activity and resulted in a pH-shift from below 7 to 10.6 within the cyanobacterial zone. Since the solubility of silicate increases rapidly above pH 9, the alkalinisation as a result of photosynthesis-induced alkalisation is seen as the motor of the exfoliation weathering of sandstone in the investigated ecosystem.

Several total element contents, namely Al_t, K_t, Mn_t, but also Ti_t, Fe_t and Zn_t are significantly increased with BSC-impact at least in the first centimetre of topsoil. This is clearly linked to the higher amounts of fine-particles such as fine and coarse silt in the top centimetre of BSC-affected topsoil. The above-mentioned total element contents correlate positively with different silt-species indicating that silty dusts are captured by the sticky surfaces of BSC which leads to an enrichment and patchy distribution of these elements. Other total element contents such as Pb_t and Sr_t rather correlate with coarser particles such as the total sand fraction and are significantly decreased on BSC-sites. Texture effects similar to the findings presented here had been reported by Malam Issa *et al.* (2001) and Blank *et al.* (2001).

Most interesting were the differences between BSC and non-encrusted soil with regard to EC and watersoluble salts. Here, it becomes obvious again that BSC-sites might be more strongly leached, longer stabilised microsites. But above this, a second process might be deduced from the findings: obviously, BSCs alter the salt contents according to an optimum that in turn depends on the crust inhabiting species. Further indices for either increases or decreases of elements and substances are found in literature. Generally, BSCs secrete several compounds that exhibit an impact on nutrients in the surrounding medium as reviewed by Harper & Belnap (2001):

- *extracellular polymers* that modulate metal-ion concentrations at the microbial cell surface by providing both cationic and anionic metal binding sites that differ in affinity and specificy. These polymers can attract and thus concentrate growth-promoting nutrients that are present at low concentrations in the surrounding environment. Those may be Na, K, Mg, Ca, Mn, Fe, Ni, Cu and Zn. According to Geesey & Jang (1990), most adsorbed metals stay on or within the extracellular sheath and remain available to vascular plants.
- *metal chelators* such as siderochromes. As found out by Paerl (1988), these effectively sequester essential trace metals in available form from environments in which metals occur at exceedingly low ambient concentrations which is especially important in soils of high pH, where some trace elements such as Mn or Zn are readily immobilised. Paerl (1988) further suggests, that for freshwater algae, it may be possible, that such chelators can be effective in harvesting essential metals from weaker natural organic chelators
- *peptide nitrogen* and *rivoflavin*. Together with siderochromes, these substances form complexes with tricalcium phosphate, Cu, Zn, Ni, and ferric iron, keeping them plant available.

Further indices for this assumption are found in phycological studies: very recently cyanobacteria were tested upon their ability to improve desert soil properties. Obana *et al.* (2007) applied the terrestrial cyanobacterium *Nostoc* to material of a brown forest soil and cultivated the samples in desert outdoor conditions for 90 days. The authors found, in accordance with other works cited above, increases of watersoluble C and N within the first 2.5 cm of soil. They did not find a significant difference of other soil properties such as exchangeable cations or pH; however, although not significant, mean values of EC and exchangeable Na, K and Ca were decreased in the first 2.5 cm. It could be possible that in this experiment as well, a tendency of decreased EC and maybe even cations could have become significant after a longer incubation time, although this assumption remains highly speculative.

Nisha *et al.* (2007) applied multi-strain biofertilisers consisting of three indigenous cyanobacterial isolates in pot-house experiments on organically poor semi-arid clay-loam soil in India (pH 7, EC=800 μS/cm, total organic carbon (TOC)=0.34%). They also found no significant differences with regard to EC after 90 and 240 days of incubation. More to the contrary to Obana *et al.* (2007), mean values of EC are slightly increased.

Earlier, Apte & Thomas (1997) tested the possibility of ameliorating coastal saline soils with the halotolerant cyanobacteria *Anabaena torulosa* in India. They found out that *Anabaena* reduced EC by 21 to 34%. By application of a radiotracer (^{22}NaCl), they could detect the processes behind this finding: Over 90% of the total cell-bound radioactivity was found to exist in a freely exchangeable state and held by the extracellular mucopolysaccharide sheath of the cyanobacterium. Previously, it had been found out that most cyanobacteria such as *A. torulosa* do not accumulate high intracellular concentration of Na^+ but respond to salinity by exclusion of the cation from cytoplasm and synthesis of certain specific stress proteins (Apte *et al.*, 1987). Thus, Na^+ remains extracellular or osmotically active, decreasing EC and reducing availability of the Na^+ to crops but releasing it back into the soil subsequent to the death and decay of the cyanobacterium.

Thus, depending on the species inhabiting soil crusts, several kinds of accumulation and depletion of nutrients and salts are possible. Results of the present study implicate that where the EC-niveau is low, such as on the Matrix site of the Accumulation Zone (AC-MA) and - when regarded independently from the bare soil - on the BSC unit of the Western Slope Matrix site (WS-MA), the top centimetre of soil is enriched with salts despite the generally stronger leached BSC-sites. On the other hand, on sites with higher base contents of salts such as the Matrix 2- and the Heuweltjie-Margin site of the Lower Eastern Slope (ES-MA2 and ES-HM), BSC-species do not accumulate watersoluble species, so that due to previous and continuing leaching on these more substantially stabilised sites, soil below BSC is depleted. It could be concluded that in low EC-ranges, the accumulation of salts can be handled and actively implemented, while in higher ranges salts become harmful and only microsites that are both, stabilised and already leached to a certain degree, are suitable locations for crust establishment.

4.4.5 Variability on D4-Scale: Mutual Dependencies between Dwarf Shrubs and Soil Properties

On several sites, the effect of dwarf shrubs on soil properties was tested. The aim of the study was a comparison of plant influence in general, and not of particular species. However, in some D3-units only one species occured and was sampled. In others, the samples were derived from canopies of mixed species. Altogether, the samples were taken on five sites, which are listed with their corresponding species as follows:

- Mountain Top, Upper Rock Fringe-unit (MT-RF); plant species: *Stoeberia utilis* (the only species on this D3-unit)
- Mountain Top, Lower Matrix-unit (MT-MA2); plant species: *Ruschia versicolor* (the only species on this D3-unit)
- Western Slope, Matrix-unit (WS-MA); plant species: *Meyerophytum meyeri, Zygophllum cordifolium, Drosanthemum hispidum*
- Lower Eastern Slope, Heuweltjie-Centre-unit (ES-HC); plant species: *Ruschia cyathiforme*
- Lower Eastern Slope, Heuweltjie-Margin-unit (ES-HM); plant species: *Ruschia cyathiforme, Salsola spec.*

For each of the five units, five miniprofiles were sampled below Plant Canopies (P) and on adjacent Open Soils (O), which were regarded as the control group. Therefore, a total of n = 75 samples for each, Plant and Open Soil data, was available for comparing the two units in question, which were in turn distinguished with regard to three sampling depths 0-1, 1-5 and 5-10 cm.

4.4.5.1 Significance Tests within the complete Data Set

Soil samples below Plant Canopies and adjacent Open Soil were compared after standardisation of the separate layer data to equal the initial conditions that are based on different site locations such as rocky areas, heuweltjies and inter-heuweltjie areas (see Chapter 2.4.5).

Tab 4.11 shows selected parameters that involve those that were tested significantly different in at least one of the three different data bases. According to the data, dwarf shrubs significantly raise the pH-value of soils within their crown area by 0.4 - 0.7 pH units with slight increases with depth. C_{org} values are also increased below Plant Canopies, but only within the first centimetre of topsoil. However, here, the amount of C_{org} is considerably increased by 1% C_{org}-content. The same is valid for N_t: in the first centimetre an enrichment of 0.05% is found below shrubs compared to adjacent Open Soil which is several orders of magnitude higher than the difference of N_t in 1-5 and 5-10 cm depth.

	0-1 cm		1-5 cm		5-10 cm	
Parameter	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH_{H2O}	50	0.37 * ± 0.54	50	0.40 * ± 0.48	49	0.70 * ± 0.57
pH_{CaCl}	50	0.51 * ± 0.51	50	0.56 * ± 0.72	49	0.65 * ± 0.82
C_{inorg}	20	-0.18 * ± 0.12	20	-0.16 * ± 0.13	20	-0.14 * ± 0.16
C_{org} [%]	50	1.00 * ± 2.06	50	0.02 ± 0.58	49	-0.12 ± 0.64
N_t [%]	50	0.047 * ± 0.070	50	0.005 ± 0.029	49	-0.008 ± 0.030
C/N-ratio	50	0.96 ± 3.8	50	-0.7 ± 1.7	49	-0.84 ± 2.5
P_{dl} [g/kg]	19	-0.07 ± 0.09		-		-
K_{dl} [g/kg]	19	0.22 * ± 0.31		-		-
K_{we} [mg/l]	20	29.8 ± 37.7	20	20.7 ± 21.5	20	4.1 ± 16.4

Tab. 4.11: Comparison of Open Soil and Plant Canopy soil for the three individual layers. Presented is the difference of mean of Plant Canopy samples compared to Open Soil after standardisation of the data set (explanation see Chapter 2.4.5). Negative values indicate lower contents on Plant Canopy sites compared to Open Soil.

C/N-ratio is considerably lower below plants within deeper layers of the topsoil but wider in the first centimetre, although this is in not significant; plant-available K (K_{dl}) is significantly higher, plant-available P (P_{dl}), however, lower, though here again this trend is not confirmed by a significance test. The K_{we}-level is increased below plants with decreasing values with depth.

Texture classes were compared separately, since, for the analysis, composite samples for each layer of the five replicate miniprofiles were prepared. Again, the data was standardised for that purpose (see Chapter 2.4.5).

Generally, the texture analyses indicate an enrichment with particles $> 200\ \mu m$ below Plant Canopies compared to adjacent Open Soils, which in addition is strongest in the surface layer and decreases with depth. This is on the one hand pointed out by significant decreases of fine particles such as clay and middle silt in the first layer, on the other hand by a partly significant and otherwise in tendencies visible enrichment of middle and coarse sand.

fraction [%]	N	0-1 cm	1-5 cm	5-10 cm
clay	5	-1.80 * ± 1.96	-2.14 ± 1.88	-0.75 ± 1.57
silt	5	-3.50 ± 3.66	-0.91 ± 2.11	-0.68 ± 1.69
fSi	5	0.07 ± 0.46	-0.31 ± 1.02	0.38 ± 0.4
mSi	5	-1.57 * ± 1.16	-0.21 ± 0.67	-1.27 ± 1.3
cSi	5	-2.00 ± 4.13	-0.39 ± 1.73	0.21 ± 1.54
sand	5	5.30 ± 5.2	3.05 ± 3.1	1.43 ± 3.05
fS	5	-3.55 ± 7.07	-0.01 ± 3.35	1.18 ± 2.66
ffS	5	-2.19 ± 3.58	-1.05 ± 2.68	2.71 ± 3.74
cfS	5	-1.36 ± 4.14	1.03 ± 1.07	-1.54 * ± 1.72
mS	5	3.47 * ± 2.86	2.84 * ± 1.12	0.78 ± 1.73
cS	5	5.37 ± 9.45	0.22 ± 4.37	-0.53 ± 2.23

Tab. 4.12: Comparison of particle size distribution of Open Soil and Plant Canopy soil within three individual layers: difference of mean of Plant Canopy samples compared to Open Soil after standardisation of the data set. Means are presented with standard deviations.

4.4.5.2 Significance Tests within Individual Sites

When looking at the parameters with regard to the individual sites, it is shown that some of the above-reported findings are valid for all sites tested, while others are varying strongly with regard to sampling location on D3 and D2 units.

Most consistent are the results of pH_{H2O} and pH_{CaCl2}: with only few exceptions, mean pH-values are increased below Plant Canopies compared to adjacent unaffected soil in all sites and in all layers. EC-values that did not show significant effects of plants on soil when data was evaluated in total after standardisation, rather did when regarding the five sites individually: on the two sites on the Mountain Top (MT), plants accumulated salts in their crown area. This was especially true for samples in the Rock Fringe zone (MT-RF1) where differences of $EC_{2.5}$ were considerable though not significant due to the small sample number and high variability. The same tendency is clearly visible on the Matrix-unit a few metres further downslope (MT-MA2).

The site on the Western Slope Matrix (WS-MA) featured the strongest differentiation in EC-values between Open Soil and Canopy soil: two of three layers showed significant differences although varying strongly within each unit. This striking difference bears resemblence with the results of BSC and Open Soil discussed in the previous chapter. The Heuweltjie-Centre on the Lower Eastern Slope (ES-HC) showed rather decreased EC-values below plants except within the first centimetre, where both, $EC_{2.5}$ and EC_5 were increased. On the Margin-unit of the same heuweltjie (ES-HM), differences between Plant Canopies and Open Soil were not clearly distinguishable, though it can be stated that on both D4-units EC-values increased with depth.

Inorganic carbon was only found in considerable amounts on the heuweltjie sites due to different parent material. Variability with depth was low, either in ¿Open Soil and below Plant Canopies. However, amounts were often decreased on the Plant Canopy sites, though not significantly. C_{org} and N_t generally decrease on all sites and both D4-units with depth. The effect of plants depends on depth: while in the first layers C and N are increased or - in one case equal - in Canopy soils, the contents show a tendency to decreased values with depth. On two sites, the Matrix of the Western Slope (WS-MA) and the Heuweltjie-Center of the Lower Eastern Slope (ES-HC), the C- and N-contents remain still above the level of the control soil. In the three units with highest slope impact, namely the two Mountain Top (MT)-sites and the Heuweltjie-Margin of the Lower Eastern Slope (ES-HM), Plant Canopy soils reach even lower C and - except on the Matrix-Unit of the Mountain Top (MT-MA2) - lower N-values than Open Soil. It should be noticed, that C_{org}- and N_t-values are much higher on the Mountain Top - Rock Fringe (MT-RF) compared to the other sites.

The C/N-ratio in general is much narrower and with that favourable in the two heuweltjie sites compared to Mountain Top (MT) and Western Slope (WS) sites. Locally, plants contribute to a significant increase of C/N-ratio (Mountain Top Matrix: MT-MA2, Lower Eastern Slope Heuweltjie-Center: ES-HC) in the first centimetre of soil. On the Mountain Top Rock Fringe-site (MT-RF), C/N-ratios are decreased below plants in all layers, which tends to also be true for the Western Slope Matrix (WS-MA). However, in other sites the opposite effect is true. In 5-10 cm depth, no significant trends could be detected.

		pH$_{H2O}$		pH$_{CaCl}$		EC$_{2.5}$ [µS/cm]		EC$_{5}$ [µS/cm]	
Site	**Layer**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**
MT-RF	**0-1**	7.0 ± 0.5	7.3 ± 0.4	6.5 ± 0.5	6.8 ± 0.4	686 ± 814	1583 ± 886	396 ± 470	970 ± 489
	1-5	6.2 ± 0.8	7.0 ± 0.5	5.5 ± 0.9	6.4 ± 0.6	822 ± 675	1176 ± 186	478 ± 364	851 ± 286
	5-10	5.5 ± 1.0	6.8 ± 0.6	5.2 ± 1.0	6.4 ± 0.6	1006 ± 417	1121 ± 528	595 ± 233	815 ± 459
MT-MA2	**0-1**	7.2 ± 0.4	7.3 ± 0.2	**5.8* ± 0.5**	**6.8* ± 0.4**	174 ± 149	514 ± 675	107 ± 87	300 ± 381
	1-5	6.9 ± 0.4	7.4 ± 0.6	**5.7* ± 0.2**	**6.6* ± 0.5**	300 ± 310	362 ± 394	228 ± 283	222 ± 206
	5-10	6.5 ± 0.6	7.1 ± 0.7	5.5 ± 0.4	5.9 ± 0.9	198 ± 167	252 ± 212	160 ± 167	146 ± 115
WS-MA	**0-1**	**6.0* ± 0.3**	**6.5* ± 0.7**	**5.7* ± 0.3**	**6.6* ± 0.5**	**1656* ± 1009**	**289* ± 316**	**976* ± 594**	**201* ± 200**
	1-5	5.5 ± 0.3	5.9 ± 0.3	5.2 ± 0.3	6.2 ± 1.1	**1778* ± 852**	**430* ± 513**	**1094* ± 559**	**291* ± 332**
	5-10	5.2 ± 0.5	5.6 ± 0.4	4.8 ± 0.3	5.9 ± 1.1	1452 ± 572	434 ± 655	878 ± 318	271 ± 393
ES-HC	**0-1**	9.1 ± 0.2	9.0 ± 0.2	7.8 ± 0.1	8.0 ± 0.1	221 ± 9	283 ± 80	164 ± 7	223 ± 58
	1-5	9.4 ± 0.3	9.4 ± 0.1	8.1 ± 0.1	8.2 ± 0.1	387 ± 69	248 ± 52	269 ± 45	202 ± 34
	5-10	**9.1* ± 0.1**	**9.7* ± 0.1**	**8.1* ± 0.1**	**8.3* ± 0.04**	641 ± 138	338 ± 40	436 ± 98	275 ± 34
ES-HM	**0-1**	**8.7* ± 0.2**	**9.6* ± 0.2**	7.9 ± 0.1	7.9 ± 0.4	185 ± 34	185 ± 60	150 ± 19	167 ± 57
	1-5	9.4 ± 0.4	9.8 ± 0.4	7.9 ± 0.2	7.9 ± 0.5	214 ± 65	211 ± 111	190 ± 45	182 ± 90
	5-10	**9.3* ± 0.3**	**9.9* ± 0.3**	8.0 ± 0.1	8.1 ± 0.5	255 ± 144	272 ± 139	228 ± 127	229 ± 140

		C$_{inorg}$ [%]		C$_{org}$ [%]		N$_{t}$ [%]		C/N	
Site	**Layer**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**
MT-RF	**0-1**	<0.01 ± 0.01	0.09 ± 0.16	3.9 ± 1.0	4.4 ± 0.7	0.21 ± 0.04	0.27 ± 0.05	18.4 ± 2.1	16.6 ± 0.9
	1-5			3.2 ± 0.3	2.9 ± 0.3	0.18 ± 0.02	0.18 ± 0.02	17.4 ± 1.5	15.6 ± 0.9
	5-10			2.7 ± 0.3	2.2 ± 0.7	0.15 ± 0.01	0.13 ± 0.03	17.9 ± 0.7	17.3 ± 2.0
MT-MA2	**0-1**	<0.01 ± 0.01	0.01 ± 0.01	**1.2* ± 0.2**	**3.2* ± 0.9**	**0.08* ± 0.01**	**0.16* ± 0.04**	**15.7* ± 1.6**	**19.2* ± 1.4**
	1-5			1.1 ± 0.3	1.5 ± 0.3	0.07 ± 0.02	0.10 ± 0.01	15.2 ± 1.4	15.5 ± 1.1
	5-10			1.1 ± 0.5	1.00 ± 0.4	0.07 ± 0.02	0.07 ± 0.02	16.2 ± 2.4	13.9 ± 2.9
WS-MA	**0-1**			**1.1* ± 0.2**	**1.5* ± 0.2**	**0.08* ± 0.01**	**0.12* ± 0.01**	14.4 ± 0.7	13.3 ± 1.2
	1-5			1.5 ± 0.3	1.5 ± 0.7	0.08 ± 0.02	0.09 ± 0.03	17.1 ± 0.8	15.3 ± 1.8
	5-10			1.2 ± 0.1	1.4 ± 0.7	0.07 ± 0.01	0.08 ± 0.03	18.0 ± 0.7	17.5 ± 3.6
ES-HC	**0-1**	0.64 ± 0.05	0.48 ± 0.12	1.5 ± 0.3	3.7 ± 4.4	0.13 ± 0.03	0.20 ± 0.13	**11.3* ± 0.4**	**15.1* ± 6.9**
	1-5	0.66 ± 0.08	0.49 ± 0.15	2.0 ± 0.8	2.2 ± 0.9	0.14 ± 0.03	0.16 ± 0.04	13.4 ± 2.2	13.8 ± 2.5
	5-10	0.69 ± 0.07	0.53 ± 0.19	1.4 ± 0.4	1.6 ± 0.8	0.11 ± 0.02	0.12 ± 0.04	12.4 ± 2.5	12.7 ± 2.5
ES-HM	**0-1**	0.36 ± 0.20	0.17 ± 0.12	1.1 ± 0.1	1.1 ± 0.5	0.11 ± 0.01	0.10 ± 0.04	10.2 ± 0.1	10.6 ± 1.5
	1-5	0.35 ± 0.18	0.19 ± 0.14	0.9 ± 0.1	0.7 ± 0.3	0.09 ± 0.01	0.07 ± 0.03	10.4 ± 0.4	9.8 ± 1.2
	5-10	0.30 ± 0.12	0.17 ± 0.14	1.0 ± 0.2	0.5 ± 0.3	0.09 ± 0.02	0.06 ± 0.02	10.3 ± 0.8	9.3 ± 1.3

Tab. 4.13: Comparison of Open Soil (O) and Plant Canopy soil (P) on the individual sites. Data are presented of selected parameters and for the individual layers. Superscripts * indicate significant difference on Plant Canopy compared to Open Soil. Means are presented with standard deviations.

4.4.5.3 Total Element Contents

Total element contents as investigated for the comparison between sites affected by BSC and adjacent Open Soil areas, were only partly available for the same analysis of dwarf shrub influence on topsoils due to a long-term malfunction of the analysator. Therefore, comparison between Canopy and Open Soil could only be drawn for two sites in the mountaineous area, the Rock Fringe (MT-RF1) and the Matrix (MT-MA2). For a detailed analysis, the data quantity was too low, however, in single observations of the individual sites, the following trends could be detected: when applying a Mann-Whitney U test on total element contents on the Canopy and Open Soil data sets in MT-RF1, no significant differences could be tested. But when applying the same test on MT-MA2, several significant differences were detectable as is depticted in Tab. 4.14.

A correlation of texture data and the mean of total element contents within the five parallel samples taken from five miniprofiles, reveals strong negative correlations between sand and Ti_t, Fe_t, Ni_t, Zn_t, and Zr_t. With the exeption of Zn_t, this finding is concordant with the accumulation of sand within the site.

D4	Layer	Al_t [%]	Na_t [g/kg]	Ti_t [g/kg]	Fe_t [g/kg]	Cr_t [mg/kg]	Ni_t [mg/kg]	Zr_t [mg/kg]	Zn_t [mg/kg]
O:	0-1	5.8* ± 0.03	17.5* ± 0.3	2.04* ± 0.15	13.4* ± 1.6	12.8* ± 1.8	7.4* ± 0.55	593* ± 97	33.8 ± 5.1
	1-5	6.0* ± 0.15	18.0 ± 0.5	2.15* ± 0.15	14.6* ± 1.7	15.2* ± 0.8	7.6 ± 0.89	581* ± 112	35.4 ± 3.3
	5-10	6.0* ± 0.11	17.7 ± 0.6	1.98 ± 0.10	13.8 ± 1.0	14.0 ± 2.6	7.0 ± 0.82	545 ± 95	32.8 ± 2.6
P:	0-1	5.2* ± 0.17	15.3* ± 0.5	1.50* ± 0.12	9.1* ± 0.8	10.0* ± 1.4	6.0* ± 0.71	193* ± 34	30.8 ± 2.1
	1-5	5.6* ± 0.15	17.1 ± 1.1	1.83* ± 0.09	11.7* ± 0.4	12.4* ± 1.7	6.8 ± 0.84	315* ± 36	34.2 ± 2.2
	5-10	5.7* ± 0.21	17.9 ± 0.7	1.90 ± 0.09	12.5 ± 0.6	11.4 ± 1.5	7.0 ± 0.71	437 ± 74	34.2 ± 7.6

Tab. 4.14: Significant differences of total element contents between Open Soil (O) and Plant Canopy (P) on the Mountain Top Matrix-site (MT-MA2).

4.4.5.4 Threefactorial Analysis of Variance (ANOVA) including all Sites

When regarding the fragmentation of total variability into the eight components (Tab. 4.15), it appears that site and residual variance amount to the strongest fractions of overall variability as was the case in the Open Soil/ BSC data set. D4-units only explain up to 7% of variability with strongest impact of K_{we} and pH_{CaCl}. While for these parameters differentiation into D4-units Plants and Open Soil is stronger than the differentiation into BSC and Open Soil, it is much less for $EC_{2.5}$ and EC_5. However, it has to be considered that the samples for the comparative studies of BSC or plant influence on soil were derived from different sites.

The Layer as the third main factor has strong influence on the variability in terms of K_{we}, N_t and C_{org}, although it explains not more than 13% of variability. The interaction of Site and Layer is less pronounced compared to the same parameters in the BSC/

Parameter	D4	Site	Layer	Site * D4	Site * Layer	D4 * Layer	Site * D4 * Layer	Residual-variance
K_{we}	7 (1)	25 (14)	12 (7)	1 (11)	3 (7)	2 (1)	2 (7)	48 (52)
pH_{CaCl2}	6 (0)	71 (89)	2 (1)	3 (0)	3 (3)	0 (0)	1 (0)	15 (7)
pH_{H2O}	2 (2)	86 (85)	1 (1)	0 (1)	3 (3)	0 (0)	1 (0)	7 (8)
N_t	2 (1)	47 (61)	13 (12)	3 (11)	4 (1)	4 (1)	1 (1)	27 (12)
$EC_{2.5}$	1 (8)	33 (24)	0 (0)	21 (28)	1 (1)	1 (0)	2 (0)	41 (38)
C_{org}	1 (1)	37 (78)	7 (2)	3 (5)	4 (2)	4 (0)	2 (2)	42 (10)
EC_5	1 (9)	31 (23)	0 (0)	22 (28)	1 (1)	1 (0)	1 (0)	43 (39)
C/N ratio	0 (3)	57 (74)	0 (5)	2 (2)	7 (6)	1 (0)	2 (0)	30 (10)

Tab. 4.15: Variance components (%) of the factors Site, D4-unit, Layer, combinations of these and non-explained residual variance. Boxes highlighted in grey represent variance components $>$ 75% of all parameters. Data in brackets represent results derived for the same analysis with the data set BSC/ Open Soil.

Open Soil data set. The percentage of unexplained variances is strikingly stronger for the parameters pH_{CaCl} (double), N_t (double), C_{org} (fourfold) and C/N-ratio (triple) all of which are linked to an inferior value by the Site-factor. For the single parameters, most strikingly deviations from the findings in the BSC/ Open Soil data set have been identified for K_{we}, were Site determines nearly twofold and D4-differentiation sevenfold the variability. pH_{H2O} is almost the same in its variance fragmentation.

4.4.5.5 Twofactorial Analysis of Variance (ANOVA) for Individual Sites

When comparing the individual sites and the variance distribution of parameters with regard to the factors D4, Layer and the interactions of those, again the most striking fact is that the factors in consideration contribute only little to variance explanation and consequently, the residual variance is high. The factor Layer is generally explaining more variability than the differentiation into D4 samples which is in contrast to the findings of the same analysis applied to the BSC/ Open Soil data set in Chapter 4.4.3.4.

Very obvious is the special characteristic of the site Western Slope Matrix (WS-MA). In many parameters this site reflects deviations from general trends mirrored in the four other sites: pH_{H2O}-values do not show interactions between D4 and layer samples as visible in the other sites; regarding $EC_{2.5}$, D4 contributes five times as much to overall variability than on other sites and dominates variability. For K_{we} and C/N-ratio variance explanation by the factor Layer is above average, and with regard to NO_{3we} factor D4 is exceedingly high represented. C_{org} is in total exceptionally weakly explained by the two factors which is due to a high internal group variability.

Another striking site is the Rock Fringe on the Mountain Top (MT-RF) showing a high variance explanation with regard to the factor Layer in terms of C_{org}, N_t, and NO_{3we}. Two sites, the Heuweltjie-Margin on the Lower Eastern Slope (ES-HM) and the Matrix on the Western Slope (WS-MA) have also been tested for variance distribution on the BSC/ Open Soil data set. ES-HM is interesting with regard to organically derived parameters such as C_{org}, C/N-ratio and NO_{3we}. The data indicates that the differentiation into Open Soil and soil below Plant Canopies generates a smaller percentage on variance than the differentiation into BSC and Open Soil. In other words: the means of Plant Canopy soils and their corresponding Open Soils deviate less than the means of BSC affected soil samples and adjacent control sites.

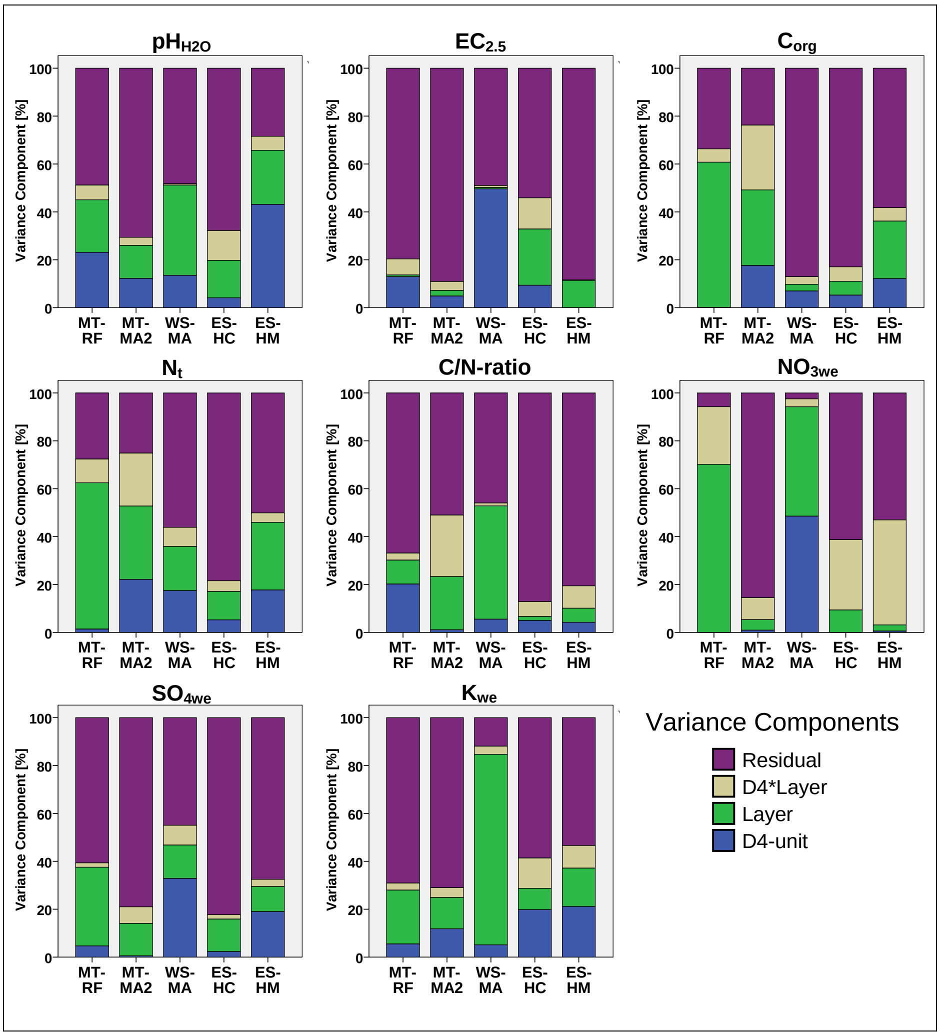

Fig. 4.13: Variance components of the factors D4-unit, Layer, combinations of these and non-explained residual variance determined by a two-way ANOVA for the separate sites.

4.4.6 Discussion of Mutual Dependencies between Dwarf Shrubs and Soil Properties

In semi-arid and arid ecosystems shrubs and trees are widely known to exert an influence on small scale variability by accumulating nutrients below their canopies, leading to enriched patches in the landscape widely referred to as "islands of fertility". The development of these patches was commonly attributed to overgrazing and desertification (Schlesinger *et al.*, 1990). Publications on the geochemical nature of fertility islands are documented frequently and worldwide, involving various species. Strong evidence is given that the kind and degree of mutual dependencies between shrubs and soil vary among species and biomes. In the Mu-us desert of inner Mongolia Hirobe *et al.* (2001) compared the soil alteration below two dominant shrubs that differed in their traits. The authors demonstrated that soil properties were spatially variable and in parts distinct below and between shrubs and, furthermore, in comparison between the different traits. Stock *et al.* (1999) compared canopy soils of several shrub-species in Rietfontein, Namaqualand, and found certain enrichments depending on the regarded species; the authors suggest that islands of fertility are stronger developed below long-lived shrubs such as *Stoeberia utilis*, a species that also exists on the Soebatsfontein Observatory. And in Paulshoek, Namaqualand, Allsopp (1999) found different characteristics in fertility islands below *Galenia africana*, *Eriocephalus ericoides*, *Ruschia robusta* and *Drosanthemum hispidum*. However, Vinton & Burke (1995) suggested that the importance of plant presence on local soil properties may overshadow that of plant species in naturally established vegetation in arid regions since decomposition and nutrient availability are primarily limited by water and not by plant species-mediated characteristics such as litter quality.

In the present study, five sites were investigated and although no particular focus was placed on species but rather on the general influence of plants per se, on two study sites (Rock Fringe and Matrix of the Mountain Top: MT-RF and MT-MA2) samples were taken below canopies of the same species which were identified as *Stoeberia utilis* and *Cephalophyllum versicolor*, respectively. On the other three sites, the species under which samples were taken varied although at each location one species dominated the data set: on the Western Slope Matrix-unit (WS-MA), three of five canopy miniprofiles were sampled below *Meyerophytum meieri*, and on the heuweltjie-sites of the Lower Eastern Slope ES-HC and ES-HM four and three, respectively, samples were taken under *Cephallophyllum inaequale*.

PH-values were most clearly discernable to be altered by plants. On all sites, and therefore independent of the particular species, pH-values were increased. Moreover, this finding applied at least in tendencies to all layers and the combined data set. Mean increases below canopies ranged between 0.1 and 1.2 in pH_{H2O} with only few exceptions. Regarding the combined data set, a mean increase of 0.5 pH-units measured in water indicates comparable effects to pH-modification by BSC (Chapter 4.4.3). This result is consistent with the findings of Stock *et al.* (1999), and partly with Allsopp (1999), who reported of increased pH-values below *Galenia africana* but could not find alteration of pH-values below four other species.

More frequently, fertility islands were reported to have increased N-contents (Stock *et al.*, 1999; Hook *et al.*, 1991; Allsopp, 1999; Virginia & Jarrell, 1983; Halvorson *et al.*, 1997). This only partly corresponds with the results for Soebatsfontein. In fact, N_t was significantly increased in the first centimetre with $p < 0.05$ but only in tendencies for other layers, and not on the Heuweltjie-Margin site on the Lower Eastern Slope (ES-HM) where rather the opposite was true. C_{org} values were strongly increased within the first centimetre of soil, but otherwise varied strongly with regard to sampling depth and site location. Accordingly, the C/N-ratio was generally lowered in fertility islands except within the first centimetre, which can be attributed to undecomposed fine litter particles. In other studies, the high variability and the enrichment of C_{org} through litter fall and increased decomposition rates was verified (Hook *et al.*, 1991; Stock *et al.*, 1999).

Also, independently from the species, texture was altered below plant canopies with a strong increase of coarser particles, especially the middle sand fraction in the size of 0.2 - 0.63 mm. Prevalently, fertility islands were reported to differ in particle size distributions from open soils. However, accumulations of texture fractions had been found by other authors in either direction, accumulation of coarse fractions and increased amounts of the fine fraction, especially including silt. Creosotebush canopies (*Larrea tridentata*) in New Mexico had higher percentages of both coarse sands and silts (Elkins *et al.*, 1986). In the Mojave desert, varying shrub species including *Larrea tridentata* had significantly lower silt-contents in soil samples taken in the 0-20 cm layer below their canopies (Titus *et al.*, 2002). Dunkerley (2000a) reports of *Maireana*-shrub mounds that have more sand, and less silt and clay contents compared to interspace samples. In sandy lands of Northern China, however, Su (2005) recorded significant increases of silt, fine sand and clay below *Artemisia halodendron*- and *Caragana microphylla*-shrubs. The authors referred this to trapping of wind-blown fine materials and dust. On the other hand, the accumulation of coarse particles below shrubs, as is the case in the present study, may be referred to rolling and saltation movements and runoff processes driven by wind and water (Sterk, 2003; Shachak & Lovett, 1998).

EC-values were inconsistent in the data set and evidence is given that this parameter is strongly controlled by the species rather than the actual presence or absence of plants. When applying a Mann-Whitney U test to Open Soil and Plant Canopy data involving all layers and all sites, no relevant significance could be found for EC. But when applying the test separately for the five sites, all kinds of interaction were detectable: the heuweltjie sites ES-HC and ES-HM on the Lower Eastern Slope showed no differences or reductions. The Western Slope Matrix (WS-MA) revealed strong increases below plants. But it must be considered that this site showed strongest differentiations with regard to many parameters and as well in the BSC/ Open Soil data set, which provides substantial evidence that here other factors may play a role such as microtopography. Most interesting, however, are the sites that are located on the Mountain Top: on both sites, the Plant Canopy samples have been taken under the same species, identified as *Stoeberia utilis* on the Rock Fringe (MT-RF) and *Ruschia versicolor* on the Matrix (MT-MA2), respectively. On both sites, means of $EC_{2.5}$ were decreased below canopies, although not significant and highly variable for MT-MA2.

For MT-RF, however, the increase in EC below *S. utilis* was tested significant on $p < 0.05$ niveau for all layers, and with $p < 0.1$ for the first layer. No comparable data could be found in literature and shall be left to other researchers to further investigate the above-described process of salt accumulation below this species.

Connected with EC are watersoluble salts that only showed a significant difference with regard to increased K_{we}-values in the complete data set. This tendency is not significant in the single layers, nevertheless the mean values show that this tendency exists throughout the first five centimetres of soil. In addition, a significant increase of K_{dl} could be detected in the first centimetre of Plant Canopy soil compared to Open Soil that corresponds with the finding for K_{we}. Since fertility islands are commonly found to be enriched with nutrients, these results deem to be expected. On the other hand, P_{dl}- values did not differ from the the control plots. Obviously phosphorus, which is much stronger limited than plant available K, is rapidly consumed by plants after deliberation through decomposition processes.

As in the observations of BSC affecting soil heterogeneity, the ANOVA analysis shows that the variability within groups, expressed by increased values of residual variance, is in many cases higher than between groups. In comparison with the BSC/ Open Soil analysis in the previous subchapter, the variability derived by plant and soil patches on the D4-scale is higher with regard to some parameters, especially for C/N-ratio, C_{org} and N_t. This may be due to litter fall and its decomposition, which is probably not only variable between sites and species but also within a group which might be referred to an unidentified factor, perhaps microtopography. A shrub that is exposed to wind or that is situated in a runoff course, might face redistribution of litter and soluble nutrients while an adjacent shrub of the same species is positioned in a safer site and accumulates litter below its crown. This hypothesis corresponds to the strongly diminished variance explanation of the Site factor compared to the BSC/ Open Soil data set: the factor Site is less important than it was in the same analysis of the BSC/ Open Soil data set and differences in the mean of the D4-units Plant Canopy and Open Soil are stronger than between BSC and Open Soil; however, since variability within these groups is high, this variation results in increased residual variance instead of a higher explanation due to D4-differentiation.

4.4.7 The Influence of Microtopography on Small Scale Soil Variability

On the Soebatsfontein Observatory, seven study sites were established and tachymetrically surveyed in high resolution with an estimated accuracy of the 3D-coordinates of < 1 cm. For each site a 3D digital elevation model (DEM) was generated with the 3D-Analyst tool in ArcGIS 9. These are based on the following density of survey points:

site name	dimension (m)	area (m^2)	survey points	density (points/ m^2)
Accumulation Area	17 x 4	68	1,559	23
Eastern Slope Heuweltjie	17 x 5	85	2,350	28
Eastern Slope Matrix	4 x 4	16	2,706	169
Western Slope Heuweltjie	5 x 9	45	2,053	46
Western Slope Matrix	5 x 5	25	1,755	70
Mountain Top	28 x 5	140	4,975	36
Mid-Eastern Slope	12.5 x 5	62.5	1,816	29
		$\sum = 441.5$	$\sum = 17{,}214$	mean = 57

Tab. 4.16: Basic data for digital elevation models (DEM) of the seven small scale study sites.

The DEMs were used to analyse the processes between micro-and mesotopography, soil properties and species distribution (dwarf shrubs, BSC). As mesotopography, the features on a D3-scale are regarded. Those are especially the slope angle of the D3-sites, for instance on heuweltjies that exhibit slope effects on the Heuweltjie-units themselves, but also on surrounding areas that may gain water and nutrient surplus by run-on processes. Similar runoff-runon interactions are expected for the Rock Fringes of the rocky outcrop areas such as Mountain Top (MT) and Mid-Eastern Slope (MS). The term microtopography envelopes the surface roughness on the D4-scale. This is created by phytogenic mounds, mounds and burrowing holes of small mammals and other patches of small uprisings and depressions. With ArcGIS 9, the course of water movement was calculated for the ideal assumption of surface water distribution at zero infiltrability. This approach gives further indices on possible effects of small scale topography on observed soil properties and species.

4.4.7.1 Micro- and Mesotopographical Description of the Small Scale Study Sites

A first approach for the characterisation of the study sites is provided in Tab. 4.17. For each D3-unit, the inclination was calculated by drawing five interpolation lines across the DEM-surface in direction of the modelled water courses. These lines were transformed into elevation profiles. Using these five profiles, a mean inclination was calculated. Approximately zero inclination was obtained for two of the three Rock

Fringe areas, although it has to be noted that the boundaries of those are diffuse and that only the first streaks of approx. 0.5 m are nearly plain.

D3-units	incl. (%)	approx. size (m)	mean h (m)	SD mean h (m)	SD mean h (%)	mean area vol (m^3/m^2)	surface to D2-area (%)
AC-HC	0	3 x 4	0.15	0.05	19	0.2	101.8
AC-HM	7	10.5 x 4	0.34	0.17	28	0.3	100.6
AC-MA	12	3.5 x 4	0.13	0.05	20	0.1	100.4
ES-HC	28	4 x 5	0.52	0.27	27	0.5	103.9
ES-HM	33	10 x 5	1.58	0.92	29	1.6	106.4
ES-MA1	23	3 x 5	0.38	0.19	24	0.4	103.8
ES-MA2	11	4 x 4	0.23	0.12	24	0.2	102.4
WS-HC	18	4.5 x 5	0.75	0.29	22	0.8	102.0
WS-HM	21	4.5 x 5	0.62	0.33	22	0.6	102.4
WS-MA	23	5 x 5	0.82	0.34	22	0.8	104.3
MT-RF1	28	4 x 5	0.75	0.44	22	0.7	114.1
MT-MA1	28	3 x 5	0.40	0.20	23	0.4	104.7
MT-MA2	30	3 x 5	0.53	0.22	23	0.5	106.2
MT-RC	32	6 x 5	0.98	0.50	25	1.0	105.9
MT-RF2	0	2 x 5	0.32	0.13	22	0.3	103.3
MS-MA1	26	1.5 x 2.5	0.26	0.10	21	0.3	104.4
MS-RF	0	1 x 5	0.32	0.10	15	0.3	104.1
MS-MA2	12	7.5 x 5	0.68	0.27	22	0.7	101.9

Tab. 4.17: Indicators of surface roughness on the D3-sites: h-diff = total height difference, mean h = mean height, SD = standard deviation (here: of mean heigt in m and %), mean area vol = mean volume per square meter calculated as volume between the 2D-area and 3D-surface area, surface to 2D-area = percentage of 2D to 3D surface. Site abbreviations see 4.1.

Also, the Heuweltjie-Centre area of the Accumulation Zone (AC-HC) was planar; however, the centre areas of the other two heuweltjies observed were not level, since on the Western Slope (WS), the heuweltjie occurred on a strongly inclined slope and was nearly completely covered in sediments, while on the Lower Eastern Slope (ES), the heuweltjie was simply too large to investigate a transect from the level top to the absolute basis of its slope. Nevertheless, even these steeper parts belong to the center as texture and chemical laboratory analysis confirm.

The Matrix site of the Accumulation Zone (AC-MA), the Lower Eastern Slope (ES-MA2) and the Mid-Eastern Slope (MS-MA2) show inclinations of approx. 11%

which reflects the overarching soft slope of the eastern flank of the observatory. On the western flank however, the basis slope matches approx. 20%; the Matrix site of the Western Slope (WS-MA) does not differ much in inclination from the adjacent Heuweltjie-units nearby, which is due to the fact that sedimentation processes on the Western Slope itself dominate over mesotopography. Strongest inclinations are obtained for the steep Mountain Top-units (MT), the Heuweltjie on the Lower Eastern Slope (ES-HM) and the upper Matrix-unit of the Mid-Eastern Slope MS-MA1.

These findings are concordant with the range of surveyed height within each of the seven study sites: The strongly sedimented heuweltjie on the Accumulation Zone (AC) features a 0.77 m height difference between the Centre and the Matrix of this transect; the reason for this low inclination is the fact that the transect was established on the mountain-facing side of the heuweltjie.

4.4.7.2 Mesotopographical Effects

The previous analysis indicated that some soil properties gradually changed when several D3-units were regarded in slope direction of a heuweltjie. Such effects are expected on transects; however, the question arose in how far gradual changes interact with the systematically and arbitrarily set boundaries of the D3-units. Therefore, the surveyed height of every single position of sampling locations was correlated with several soil properties along a chosen heuweltjie transect. The analysis in Chapter 4.4.2.3 revealed that the regarded habitats Accumulation Zone (AC), Lower Eastern Slope (ES) and Western Slope (WS), which were all structured into Heuweltjie and Matrix-units, feature substantial differences with regards to the Heuweltjie-units. Both, Accumulation Zone and Western Slope heuweltjies, are strongly transformed by sedimentation processes. Therefore, the Heuweltjie/ Matrix-composition on the Lower Eastern Slope was defined as most "typical" and deemed most suitable for the mesotopographical analysis. Here, a transect is regarded from the Heuweltjie-Center (ES-HC), over the Heuweltjie-Margin (ES-HM) to the two Matrix-units (ES-MA1 and ES-MA2).

A correlation of soil properties and height position on D2-area Lower Eastern Slope (ES) is given in Tab. 4.18. Strongest correlations > 0.7 occur between height and pH, and between height and several total element contents such as K_t, Si_t, Na_t, Ca_t, Mg_t, P_t, Mn_t, Cu_t, Zn_t and Sr_t. In most cases, the relations between height and parameter are non-linear. Linear correlations exist between height and some total element contents such as Mg_t, Mn_t, Zn_t, Na_t, Cu_t and Cr_t. While some of the parameters (pH, K_{dl}) show a gradient along the whole transect ranging from Heuweltjie-Centre to the Matrix 2 area, others only range between Centre and Matrix 1 (e.g. Ca_t, Fig. 4.14).

parameter	r^2	parameter	r^2	parameter	r^2
pH_{H2O}	0.82	Si_t	0.79	Pb_t	0.42
pH_{CaCl2}	0.88	Al_t	0.44	Ba_t	0.78
$EC_{2.5}$	0.19	Na_t (l)	0.71	Sr_t	0.96
EC_5	0.22	Ca_t	0.96	Zr_t	0.26
C_{org}	0.28	Mg_t (l)	0.91	Cl_{we}	0.00
N_t	0.28	Ti_t	0.02	NO_{3we}	0.23
C/N-ratio	-	Fe_t	0.07	SO_{4we}	0.10
S_t	0.46	Mn_t (l)	0.92	HCO_{3we}	0.60
K_t	0.85	Cr_t (l)	0.33	Ca_{we}	0.52
K_{dl}	0.28	Cu_t (l)	0.67	Mg_{we}	0.18
P_t	0.84	Ni_t	0.05	K_{we}	0.31
P_{dl}	0.61	Zn_t (l)	0.78	Na_{we}	0.13

Tab. 4.18: Correlation coefficients between topographic height and soil properties for the D2-site Lower Eastern Slope (ES). r^2-values were derived by generating fitting curves across the particular diagrams. This way, the linear or squared relation between the parameters were considered. (l) = linear relationship. All others squared.

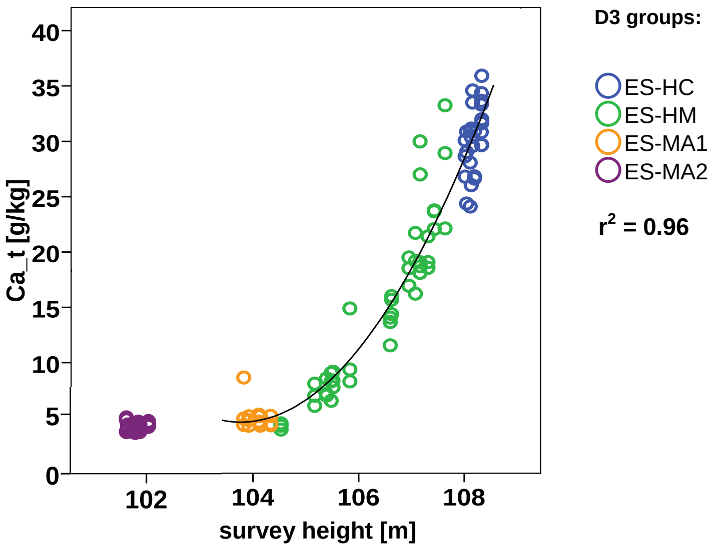

Fig. 4.14: Correlation between survey height and Ca_t on a transect on D2-Area Lower Eastern Slope (ES).

The analysis revealed an expected gradual variation of elements that is mostly connected to textural transitions along the slope angle, which the heuweltjie exhibits on its flanks. As the correlation coefficients of Tab. 4.18 indicate, some dynamic parameters are linked to texture as well: this is mainly because of the fact that in Heuweltjie-Centres carbonates are accumulated, which goes along with increased pH-values and HCO_{3we} contents. Since heuweltjies are of biogenic origin, other nutrients are also increased, for instance P_{dl}. While Mg_t shows a linear correlation with slope position corresponding to a dominating textural effect, Ca_t shows exponential relations with height since both, texture effects and carbonate accumulation in the Centre overlap.

The obtained results are only valid for "typical" heuweltjies and for transects that range not only from Heuweltjie-Centre to Matrix but are also established facing away from the general slope. The findings on mesotopographical influence are a necessary background information for the topographical analysis of the next top-down hierarchical level, following in the next section. But moreover, they further clarify the fact, that the definition of D3-units is an arbitrary process that was conducted with regard to morphological characteristics. If other key questions were in focus, for instance involving continuum aspects, these units could be determined differently. For the current study, the results indicate that D3-units cannot neccessarily be seen as homogenous units but exhibit certain trends for some parameters that are linked to slope. Therefore, mesotopography has to be considered as another factor explaining variability within a D3-unit.

4.4.7.3 Microtopographical Effects

In mesotopographical effects it could be shown that a gradual change with slope exists on typical heuweltjies. In some of these correlation graphics high r^2-values were obtained. In others, values of similar height and thus slope position varied strongly. On the above-described example, $EC_{2.5}$ was striking due to the fact that a mesotopographical trend was visible that varied much stronger when it was further focussed within each D3-unit. This was especially true for the Matrix 2 site on the Lower Eastern Slope (ES-MA2) where EC-values ranged in most cases between 25 and 250 μS/cm, while three values reach up to 1000 μS/cm. Other D3-units also varied considerably. For this example, data was observed in detail by using the digital elevation models. The general idea was that variability was due to microscale depressions and elevations, which influenced hydrological pathways and thus, the distribution of salts. On the other hand it was supposed, that D4 and the nearness to some D4-groups were important, too. Therefore, a table was generated which comprised the profile number, the associated D3 and D4-unit and a five-step classification of EC-value (strongly above, directly above, on, directly below or strongly below the mesotopographical trend represented by a fitting curve) and the microtopographical location (depression to elevation in five steps). It was assumed that higher situated areas are stronger leached while depressions show increased salt contents. Therefore, a final evaluation was done with help of Fig. 4.15 where all classes were compared with one another with regard to D4-affiliation.

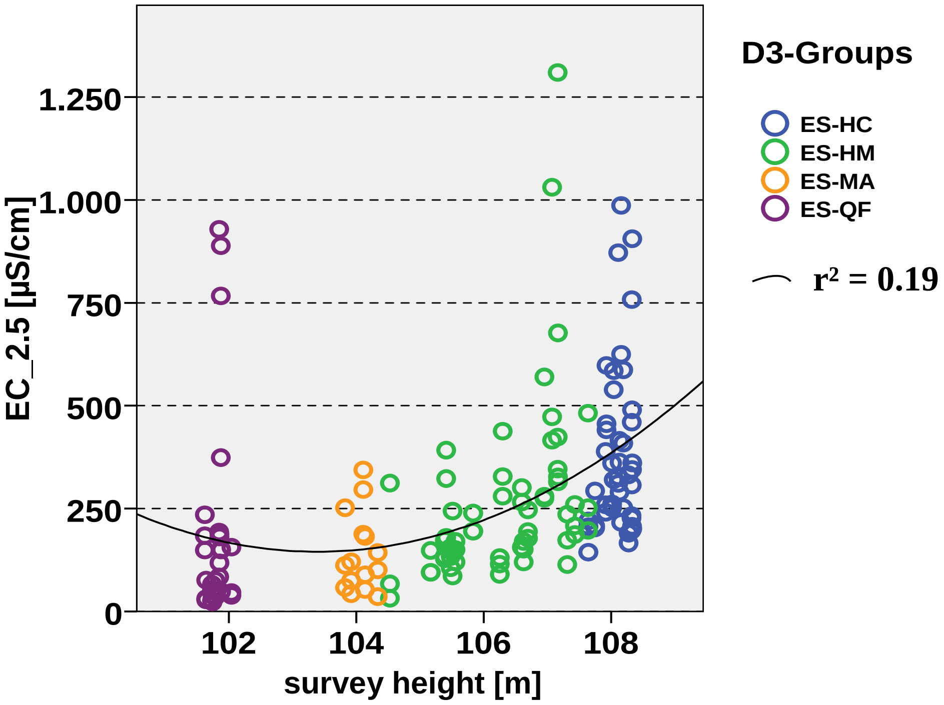

Fig. 4.15: Mesotopographical gradient and microtopographical variability of $EC_{2.5}$ on the Lower Eastern Slope (ES)-transect.

The results are deptiсted in Fig. 4.15. When regarding the accordance between microtopography and EC-value in the whole data set, no trend could be found. In a total of 50 profiles, the evaluation resulted 16 times in accordance, 19 times in non-accordance and thirteen times in no clear relation. Similar results were obtained when evaluating the data on the D3 and D4-level as well. The only D4-unit that allows the assumption of a relation is the unit "Dead Shrub" where in 6 of 10 cases an accordance could be found and only one non-accordance. In three cases, neutral decisions were made. However, the low sample quantity leaves this hypothesis unsecured.

In a second attempt, the relation between a particular D4-unit, plant canopy, and microtopography was assessed. During the field survey it was observed that under some shrubs phytogenic mounds, consisting of accumulated sediments, occurred. Further, from the analysis of Plant Canopy - Open Soil interaction in Chapter 4.4.5, certain effects between Plant Canopy and Open Soil were proved. It was hypothesised that these effects potentiate with the degree of phytomound development.

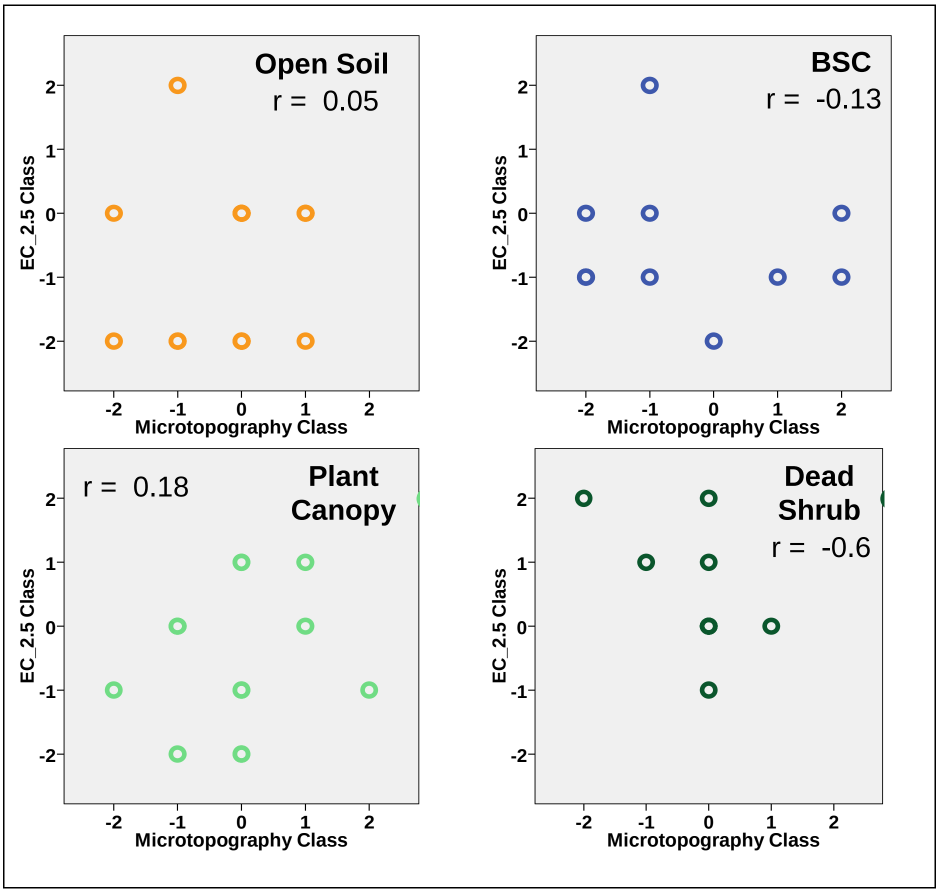

Fig. 4.16: Interrelation between EC classes and microtopography classes on the Lower Eastern Slope (ES) transect. EC-classes range gradually from -2: below r-value to +2: above r-value. Microtopography classes range gradually from -2: depression to +2: elevation.

To follow up on this assumption, the Western Slope (WS) D3-units were chosen, since only here phytomounds were at least in parts clearly developed and also sampled. In addition, the study site proved favourable because of its relatively equal inclination. Canopy samples were taken on all three units and sampled species were comparable in size and partly even occurred on all units (*Zygophyllum cordifolium*). Where phytogenic mounds were developed, mound height reached up to six centimetres. A clear statement on height was difficult since mound structure often overlapped with other microtopographical features, especially on the Matrix site (WS-MA) where alterations of differently inclined small scale areas occurred. However, in Tab. 4.19 and Tab. 4.20 mound development with regard to the species on an ordinal scala were compared to selected soil properties, that showed effects between Plant Canopy and Open Soil in previous analysis.

profile	unit	pH_{H2O}	$EC_{2.5}$	C_{org}	N_t	mound class	species
830	WS-HC-P	9.6	181	0.64	0.07	2	Z. cordifolium
831	WS-HC-P	8.7	188	1.65	0.13	1	Z. cordifolium
832	WS-HC-P	9.2	128	0.46	0.05	1	Z. cord./ P. dinteri
833	WS-HC-P	8.4	161	1.00	0.09	1	Z. cordifolium
834	WS-HC-P	9.1	197	1.28	0.12	2	Z. cord./ P. dinteri
840	WS-HM-P	9.5	249	1.12	0.10	1	Z. cordi./ P. dinteri
841	WS-HM-P	9.2	284	1.21	0.10	0	P. dinteri
842	WS-HM-P	10.1	549	0.74	0.08	0	P. dinteri
843	WS-HM-P	9.3	225	0.67	0.07	-1	P. dinteri
844	WS-HM-P	9.7	212	0.64	0.06	1	Z. cordi./ P. dinteri
1281	WS-MA-P	6.2	236	1.33	0.08	1	M. meieri
1282	WS-MA-P	5.8	358	2.42	0.12	0	Z. cordifolium
1283	WS-MA-P	5.2	1,392	1.40	0.09	2	Z. cordifolium
1284	WS-MA-P	6.1	56	1.42	0.09	2	M. meieri
1285	WS-MA-P	5.6	47	0.72	0.05	0	M. meieri

Tab. 4.19: Interrelation of selected soil properties (in weighted means over 0-10 cm depth) and developmental degree of phytomounds: phytomound classes: -1 = slightly depressed microsite, 0 = no phytomound, 1 = slight phytomound, 2 = strong phytomound (> 3 cm).

	pH		$EC_{2.5}$ (µS/cm)		C_{org} (%)		N_t (%)	
	B	P	B	P	B	P	B	P
WS-HC	9.0 ± 0.3	9.0 ± 0.5	92 ± 48^a	171 ± 28^b	0.63 ± 0.1	1.01 ± 0.5	0.063 ± 0.01	0.094 ± 0.03
WS-HM	8.7 ± 0.6 ^{a}	9.6 ± 0.4 ^{b}	150 ± 171	304 ± 140	0.57 ± 0.2	0.88 ± 0.2	0.057 ± 0.01	0 .082 ± 0.02
WS-MA	6.4 ± 0.4	5.8 ± 0.4	40 ± 11^a	418 ± 560^b	1.17 ± 0.3	1.46 ± 0.6	0.081 ± 0.02	0.088 ± 0.03

Tab. 4.20: Comparison of mean values ± SD between B = D4 Biological Soil Crust and P = D4 Plant Canopy. Calculations included weighted means over 0-10 cm of each miniprofile.

As a result, on none of the D3-units any relations between developmental degree of phytogenic mound and soil properties could be found. Conclusively, though Plant Canopy soil *per se* differed at times strongly and in cases also significantly from other units (in this case BSC), the microtopographical properties have no impact or their effects are masked by other processes.

Another approach to test interactions between microtopography and soil properties focuses on the assumption that surface roughness in terms of occurrence of depressions and elevations increases the variability of soil parameters. As a measure of surface roughness the percental relation between 2D-surface (= length times width of each D3 surface model) and 3D-surface (taking the variation in the heigth of the surface into account) of each D3-unit is determined with ArcGIS 9. This measure is correlated with the standard deviation of soil properties within each D4-group that was sampled within the D3-unit (Fig. 4.17 and Appendix Fig. A.20).

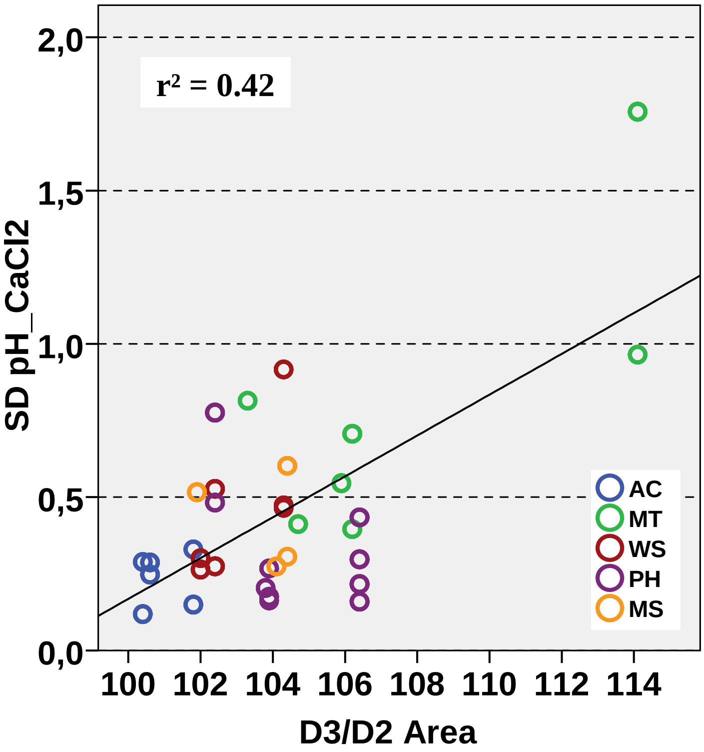

Fig. 4.17: Correlation between the surface roughness percentage and the standard deviation of pH_{CaCl2} within each D3-unit.

For some parameters there is a weak trend for this relation but this finding has to be evaluated carefully. In general, a positive interaction of surface roughness and variability represented by SD exists; however, this evaluation remains speculative, since the positive trend is to a high degree due to scatter plots that reflect the situation between roughness and variability on the Rock Fringe unit of the Mountain Top (MT-RF1): this D3-unit shows a high roughness value because a huge part of the area is characterised by phytogenic mounds of the large shrub *Stoeberia utilis*. And indeed, the only two occurring D4-units "below plant canopy" and "bare soil" exhibit a strong variability within certain values. The only problem is, that between this D3-unit and all other units a large gap exists and that in the lower surface roughnesses some D3-units follow the assumed trend but others do not. One can say that by examining these relations an influence between surface roughness and the variability of soil properties such as pH_{CaCl2}, $EC_{2.5}$ S_t, N_t and K_{we} may exist, but those are frequently masked or dominated by D4-affiliation, local disturbances and other influences.

A brief recapitulation shall be included at this point:

1. Analysis on soil properties conducted by way of example on a "typical" heuweltjie transect has pointed to a clear mesotopographical gradient of some soil properties connected to gradual textural change from centre to interheuweltjie-area.
2. Consideration of this mesotopographical gradient, the influence of microtopographical features (elevations, depressions) was tested for the example of $EC_{2.5}$ but produced no evidence for effects
3. An attempt was made to quantitatively describe the effects between soil and microtopography: the hypothesis of surface roughness increasing soil variability was tested, but did not result in a solid trends either. However, tendencies of effects are visible.

After these attempts regarding evaluations of mutual dependencies between microtopography and soil properties vastly failed, three examples shall be further examined that attracted attention by striking effects in previous data analyses. With these examples, an approach is made to show that microtopography definetely has an impact on soil properties, although this only locally appears in describable ways and cannot be measured quantitatively.

1. The D3-site Heuweltjie-Margin on Accumulation Zone

The D3-site Heuweltjie-Margin on Accumulation Zone (AC-HM) shows a striking variability of EC and associated soil properties such as Cl_{we} and SO_{4we} as well as some texture related parameters (Al_t, Na_t, Ti_t, Fe_t. See Fig. 4.9 and Fig. A.2 to A.15). When analysing the digital elevation model in detail, the cause of this becomes obvious: several mole rat mounds occur on the heuweltjie. People stumble over molehills - not mountains, sais Confucius. These disturbances were noticed during fieldwork and surveyed. It was avoided to take samples directly on the mounds, since these features were actually regarded as unrepresentative. Nonetheless, as the simulated water courses show (Fig. 4.18), several sample sites were affected by the disturbances either because they were located very close to them, or they lay below the plots within simulated runoff courses as in profile 768. As the profile data shows (see Fig. A.1 and Fig. A.2 in Appendix), the internal part of the heuweltjie consists of materials with strongly increased salt contents. This material was brought to the surface by digging animals and partly redistributed over the surface during several rain events, thus leading to the observed patchiness. This variability is regarded as a natural phenomenon that is not the exception but part of the dynamics within the ecosystem and probably one component contributing to ecosystem stability.

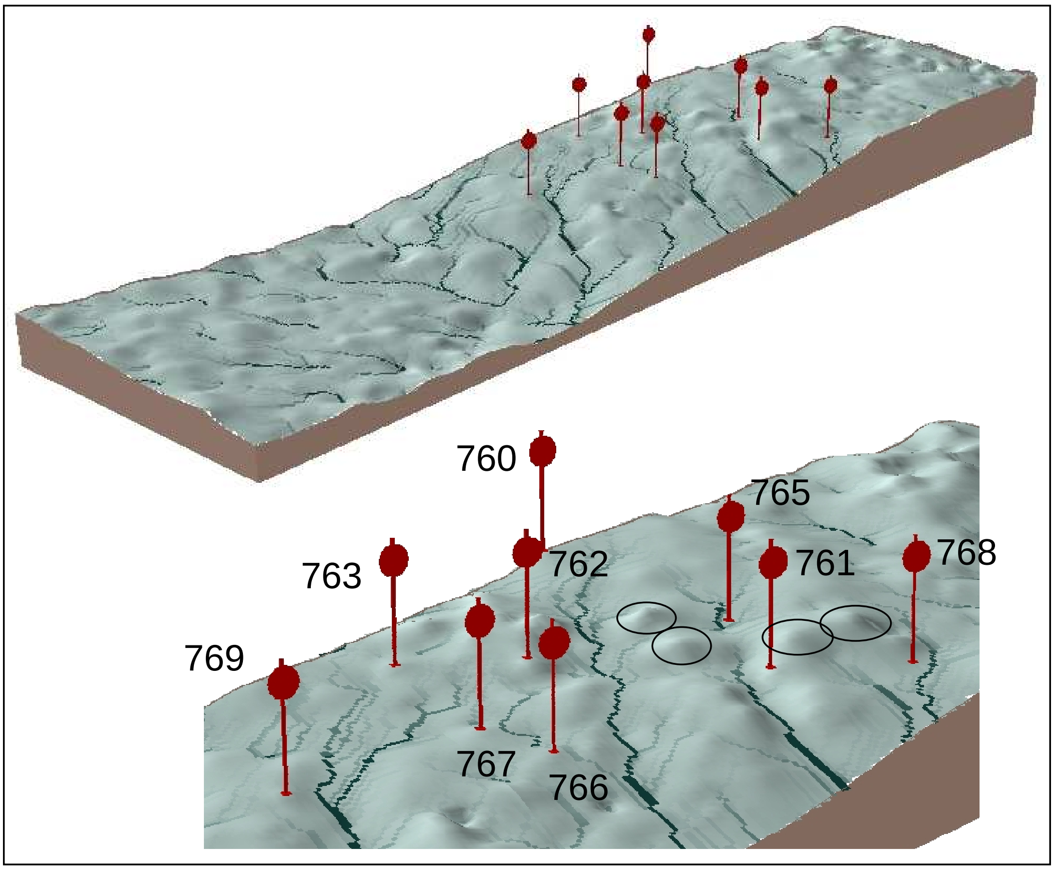

Fig. 4.18: The digital elevation model of the Heuweltjie Margin unit on the Accumulation Zone (AC-HM) in overview and detail showing the position of miniprofiles.The circles indicate the position of mole rat mounds.

profile No	D4-group	EC 2.5 [µS/cm]
760	BSC	38
761	BSC	419
762	BSC	30
763	BSC	128
765	Open Soil	330
766	Open Soil	44
767	Open Soil	159
768	Open Soil	1732
769	Open Soil	219

Fig. 4.19: Left: picture of the mole rat mounds occurring on AC-HM. Right: table with D4-affiliation and EC-values for the above-presented miniprofiles.

2. D3-site Matrix on Western Slope

The study site Matrix on Western Slope (WS-MA) proved peculiar in many ways: during the analysis of BSC and plant interaction with control sites, it was striking that many soil properties were increased, highly variable and strongly differing from other units of the D3-site. This was particularly true for EC and watersoluble anions, but in parts also for C_{org}, N_t and S_t, which unexpectedly showed increased values compared to the BSC-site.

When looking at these striking soil properties an indication becomes obvious that points to the microtopography. Fig. 4.20 shows a picture of the site taken in August 2004, when the site was sampled and surveyed. 2004 was a year with rather sparce rain and the only occurring plants on the site at that time were perennials dominated by the dwarf shrub species *Meyerophytum meyeri*.

Fig. 4.20: Overview of the study site Western Slope Matrix (WS-MA) in August 2004.

Fig. 4.21 shows detailed photos of the D4-units. The Open Soil units are clearly visible in the foreground: they stretch in parallel lines accross the site. The surface is rather smooth and more level than other units and the soil is tough and in parts crusted. Inbetween these lines, small scale areas with higher inclination occur: these exhibit a rougher surface which is covered with BSC.

Fig. 4.21: Left: view of the study site Western Slope Matrix (WS-MA): alterations of more stongly inclined and smooth, planar subunits. Right: detailed view of an inclined part: these little "slopes" are made up of plants and BSC.

The observation that the Open Soil-units are linked to microtopographically varying areas was tested with the DEM of this site. For this purpose, contour lines were drawn based on the DEM-surface and an associated hillshade raster (Fig. 4.22). One contour line was identified that divided clearly between planar and more strongly inclined areas. In a next step, a photo-stich of detailed topviews was used to delineate the canopy areas of plants which made up the second D4-unit. Since the photos were made in 2006, a fairly good rainyear, parts of the matrix are covered with herbs and the whole site looks much different compared to the pictures taken in 2004.

Finally, the three D4-units could be related to defined areas and the whole site could be subdivided into extrapolated micropatches (see Fig. 4.23). By comparing areal information and point measurements, it could be confirmed that all Open Soil sampling points matched the areal Open Soil-unit and that, conclusively, the strong deviation of soil properties measured on this site, may have its cause in the microtopography. Moreover, BSC and Plant Canopy profiles were examined further. As Tab. 4.21 shows, all BSC samples have approximately the same value and are very low in EC-values. But Plant Canopy samples are ranging strongly from 47 to 1,392 μS/cm with two profiles showing low values, two profiles featuring intermediate values and one profile with a very high value. Since samples were taken below the canopies of two different plant species, a species-specific influence may not be excluded. The highest value of profile 1283 was sampled below a *Zygophyllum cordifolium*-shrub that developed a clear phytogenic mound below its canopy. The two low values belong to canopies of *Meyerophytum meyeri*. However, the intermediate values belong to two adjacent profiles that were sampled below *Z. cordifolium* for profile 1282, and *M. meyeri* with regard to profile 1281. On the other hand, by further examination of the DEM, it can be stated, that the two intermediate profiles are located between Open Soil and BSC-areas, that the canopy with the highest EC-values overlaps with level Open Soil areas and that the profiles exhibiting low EC-values are either located on inclined areas or - in case of profile 1285 - are surrounded by them, thus protected of salt intake. Though this is no proof, it seems likely that the kind of species has an inferior influence on the EC-value and that the scattered distribution of the plants on both, planar and inclined areas, is the actual cause of variability within the D4-unit Plant Canopy soil.

The patchiness is obviously caused by erosion. The Open Soil areas are defined as eroded areas, probably initially generated by the so-called ”voetpaadjies” (Afrikaans: sheep paths) since a kraal was once located nearby. The inclined areas inbetween seem to be the remaining intact surfaces. Probably during rain events water flows stronger off on BSC-areas, as a result of both, inclination and probably sealing properties of the crusts. Since the Open Soil areas are less inclined, water accumulates here when rain ceases. The surface is sealed and water infiltrates only into shallow depths, thus avoiding leaching of imported salts. The alteration of rain and evaporation and the lack of consuming plants finally lead to salt accumulation.

Moreover, surfaces on inclined areas are washed off by rain, which explains the accumulation of C_{org}, S_t and N_t in the planar units. Probably this may be valid for salts, too, that are brought into the system with seafogs expected to be more frequent on this seawardly exposed side of the mountain.

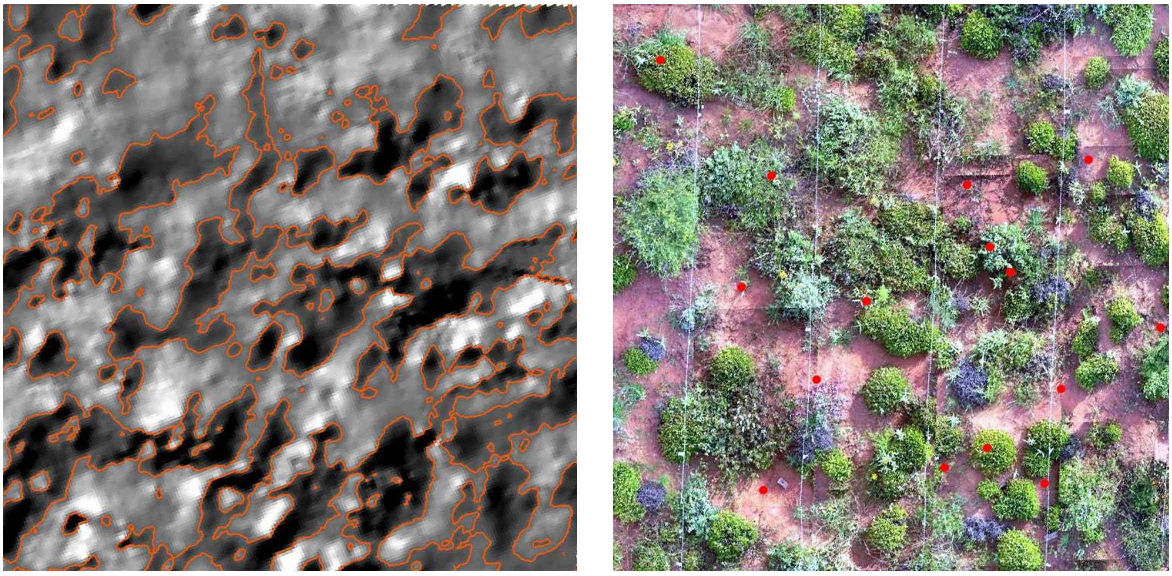

Fig. 4.22: Left: differentiation of planar and inclined areas of WS-MA with contour lines. Right: photo-stich of the same site as a basis for determination of D4-unit plant canopy (photostich by G. Miehlich, 2006). Red dots show the positions of miniprofiles.

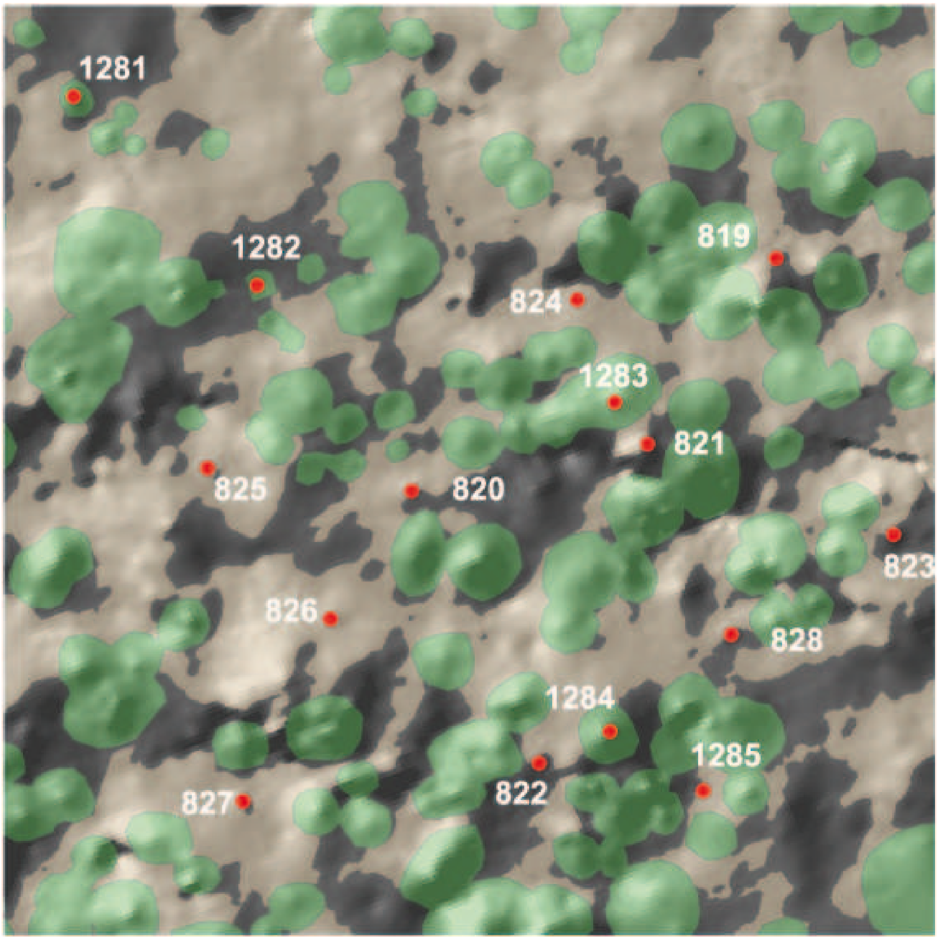

Fig. 4.23: ArcGIS-based areal distribution of the D4-units Plant canopy (green), Biological Soil Crust (grey) and Open Soil (brown) and miniprofile locations on the study site Western Slope Matrix (WS-MA).

profile no	D4-group	$EC_{2.5}$ [µS/cm]	profile no	D4-group	$EC_{2.5}$ [µS/cm]	profile no	D4-group	$EC_{2.5}$ [µS/cm]
824	O	2748	819	B	59	1281	P	236
825	O	918	820	B	31	1282	P	358
826	O	1640	821	B	35	1283	P	1392
827	O	1280	822	B	38	1284	P	56
828	O	1428	823	B	39	1285	P	47

Tab. 4.21: D4- and microscale dependent variability on the site Western Slope Matrix (WS-MA) with the example of $EC_{2.5}$. O = Open Soil, B = Biological Soil Crust and P = Plant Canopy.

3. An Attempt to explain the EC-values of the Biological Soil Crust/ Open Soil Analysis with Mikrotopography

During previous analyses the comparison between BSC and Open Soil generated interesting results. After evaluating various publications on the topic, it was expected that soils covered with BSC would exhibit higher C- and N-contents, since all kinds of BSC are known as important N-suppliers within ecosystems and some authors even suggest that these features might be the clue to the terrestrial C-gap in climate models. Also, it was assumed, that BSC might show increased EC-values since they make nutrients available and produce nitrate. But none of the assumptions proved true: while the observation of N_t did not result in any significant differences neither on the whole data set nor on single locations, the combination of all six data sets through a standardisation procedure led to a general decrease of C_{org}-values on BSC-sites. $EC_{2.5}$ and NO_{3we} were also decreased on BSC though significantly only in two of six locations, with the exemption of the D3-unit Heuweltjie-Center on Accumulation Zone (AC-HC), where - to the contrary - a significant increase of these parameters was achieved. It was concluded from these results that BSC occur on more stabilised microsites that are more strongly leached.

In this approach it was tested by the example of the parameter $EC_{2.5}$, whether this hypothesis could be confirmed with the digital elevation models. It was assumed that on the small scale, stabilised sites are characterised as planar to slighly elevated areas on the surface of the digital elevation models in contrast to slight depressions that marked run-off courses.

The only site showing significantly increased EC-values is site Heuweltjie-Center of the Accumulation Zone (AC-HC). Evaluating the sampling sites with regard to their occurrence on elevations and depressions, in four of five sites the BSC occur on slightly increased patches while Open Soil sites were sampled dominantly in slightly depressed microsites. Nevertheless, since this is the only site where BSC show higher EC-values, this finding on the one hand confirms the general assumption of BSC occurring on stabilised and comparably higher lying patches, but on the other hand it contradicts the assumption that those areas are more strongly leached. When regarding the data in detail, it becomes obvious that of the three layers only the first centimetre is significantly increased. With depth, this trend is still present but less pronounced. Also, it is known that the centre parts of heuweltjies have higher silt and salt contents and are strongly disturbed due to burrowing activities of mammals (see measure for soil roughness Tab. 4.17 and Fig. 4.18 and 4.19). Furthermore, it was stated before that BSC may bind dust particles easily on their sticky surfaces. Therefore, the combination of several factors only occurring on this special location may lead to the effect, contrary to the findings of other D3-sites: due to the increased burrowing intensity in the very silty and salt-enriched inner material of the heuweltjie centre, more dust is set free and deposited on the BSC-sites, increasing EC-values compared to Open Soil units where dust is washed off or blown easily away from the exposed site.

Fig. 4.24: The distribution of BSC on the Heuweltjie of the Lower Eastern Slope: samples of Open Soil plots marked with blue, on BSC with red triangles. Same numbers indicate same striking topographical features. Eroded areas are clearly visible on both, DEM and photo.

On the D3-sites Heuweltjie-Margin and Matrix of the Accumulation Zone (AC-HM and AC-MA) and the Matrix 2-unit of the Lower Eastern Slope (ES-MA2), sampling sites of Biological Soil Crust and Open Soil-units were found to be located on elevations and depressions alike. Also, the data analysis regarding Open Soil and BSC on these D3-units did not result in significant differences. Possibly, the assumed processes are superimposed by other effects as could be shown in the example of the increased EC-values along runoff courses below mole rat mounds. Some parameters might be too sensible, easily affected by several processes on varying scales in a highly dynamic system.

However, on two D3-units the decreased EC-values on BSC-sites were significant and strong. The Western Slope Matrix site (WS-MA) was analysed in detail above and it could be shown that the inclined areas are those less affected by erosion and thus stable. The other unit in focus is the Heuweltjie-Margin on the Lower Eastern Slope (ES-HM). When looking at the location of sampling points on the DEM depicted in Fig. 4.24, the cause for this difference might be obvious since miniprofiles of Open Soil were sampled further downslope than samples of BSC; therefore decreased values of EC might be due to a gradual change of texture along the heuweltjie slope. On the other hand, strongly developed BSCs did not occurr along the whole margin of the heuweltjie but only on certain ledges as indicated by arrows in Fig. 4.24. Since the whole flank of the heuweltjie as well as its basis is strongly eroded, these ledges remain as stable islands. Here, as on site Western Slope Matrix (WS-MA), the surface is covered with BSC and has a rough surface compared to the Open Soil areas, which are probably subject to sheet erosion.

4.4.8 Discussion of the Influence of Microtopography on Small Scale Soil Variability

The role of microtopography at a scale focused on in the present study has been barely recognised in recent literature. Most related are studies of Huang & Bradford (1992) who developed a method of quantifying soil microtopography by using a portable laser scanner with the aim of modelling erosion processes. Later, their ideas were further applied by Kamphorst *et al.* (2000) who worked on a method to improve predictability of depressional water storage by surface roughness measures, since these increase the time of infiltration and reduce runoff generation. With this method, the achieved resolution may be much higher and more precise than the surveys at hand since the soil surface has not to be touched by a bar with a prism, but is scanned by a laser beam. However, the method is appropriate for a detailed analysis of the surface soil of small areas alone, which is much beyond the scale and purpose of the present study. Yet, the potential applications discussed by Huang & Bradford (1992) apply with the coarser scale studies conducted in Soebatsfontein: the authors propose that surface boundary processes are controlled by roughness and a detailed DEM of microtopography provides information on the spatial distribution of surface processes. For soil erosion they further state that these processes are raindrop-impact effects, surface ponding pattern, flow meandering and shear, sediment deposition, wind exposure and sheltering. This applies widely for small scale studies on Soebatsfontein although here, the scale in focus is one step coarser and considerations go a bit further by embracing effects of biogeochemical processes as well, which is certainly based on the same effects that control erosion, at least when assuming that erosion starts on the very small scale.

In this chapter, several attempts were made to evaluate the effect of microtopography on soil properties. However, approaches to the formulation of overall soil-microtopography effects failed. Neither the differentiation of samples taken on elevations or depressions, nor the observation of a hypothesised relation between soil and the developmental degree of phytogenic mounds showed any effects. The same was largely true for a more general approach of correlating a measure for surface roughness with soil variability expressed as standard deviation. Only in very local and strongly pronounced cases an interaction of soil-microtopographical effects could be described. On a coarser scale, however, the so-called mesotopography, clear effects were obtained.

Several causes for the indifferent results are possible. First, the survey itself has to be regarded critically. Although the DEMs comprised of high-resolution measurements compared to other studies, the tachymeter procedure is still far from a scanning, both, in terms of precision and in error probability. The survey was accompanied by the constraint of on the one hand surveying an intact surface and on the other disturbing it in the process by stepping on it. In some cases the decision on the fact, whether a miniprofile was situated in a depression or on a very slight elevation, was difficult to undertake, when differences were not clearly pronounced. However, this concern was met by placing particular focus on very pronounced microtopographic features such as phytogenic mounds. Still, this did not lead to stronger findings.

It is suggested that in the microtopographical analysis a scale is reached were effects may still occur but are frequently superimposed by other overlapping processes. If at all, microtopographical processes on this scale are only detectable with a much higher sampling amount and a sampling scheme that focuses on uniform microtopographical features with regard to constant D4, D3 and D2-association. However, this may still be difficult since for instance microscale rins, as calculated with ArcGIS 9 on the DEM, are not easily determined under field conditions.

It is further assumed that a miscellaneousness of interfering units, features and processes of varying scales sums up to a variability that is practically not quantifyable from a certain scale top-down. The here regarded scale of microtopography seems to be this transition zone where most processes and interactions dissolve into a single background heterogeneity. Very dynamic processes such as salt accumulation, measured for instance as EC, may depend on far more than surface roughness. Cracks within surface crusts, variability in plant species composition and developmental stage of biological soil crusts, or simple disturbances of the surface by animals, may decide upon local modifications of infiltration rates that additionally depend on rain intensity, duration and erosivity as well as the previous condition of the surface in terms of prewetting. Subsurface pore and root systems may control the water distribution in soil sublayers, plant consumption of nutrients and water may locally lead to an alteration in soil properties.

Another important aspect is site history. Halvorson *et al.* (1997) speak of the term ”ghost islands”, for spots that were formally vegetated with plants. In their study on *Artemisia tridentata* shrubs in a cool desert in the USA, they still found significant effects of the plant on soil patterns nearly a decade after the plants were destroyed by fire. The authors state that ”these patterns are a significant source of soil variability that may be difficult to account for because they are not related to the obvious location of live plants”. Stubbs & Pyke (2005) found similar effects in central Oregon, USA. While a removal of the plants resulted in the same fertility island effects as on an untreated control plot, a removal of the plants by fire even increased the concentration in the former canopy areas. Since in Soebatsfontein dead shrubs decay, it is likely that a modified elemental composition of the soil is measurable although such a ”ghost island” is beyond morphological identification. The same is conceivable for animal impact. In the example of the Accumulation Zone (AC), it could be shown that digging activities of small mammals may locally and probably in time increase the variability of certain soil parameters considerably. After some time, these observed mounds will diminish to another kind of ghost island, which shows no or a barely recognisable morphological difference compared to the rest of the soil surface but may still exhibit different soil properties. Also, excrements belong into this category.

In arid and semi-arid ecosystems, depressional water storage may lead to a redistribution of salts and elements on the surface, which may again - depending on rain intensity - result in salt accumulation or leaching. Two scenarios are conceivable: often, winter rainfall events in Soebatsfontein were experienced as very light rains, only percolating a few centimetres into the soil. In such cases salts are not leached downward, but are translocated upwards again with evaporation, which may lead to a slight salt accumulation after several of such wetting/ drying cycles. Depending on what kind of surface surrounds a depression, surface runoff is generated and elements and dust particles are redistributed. BSC for instance are reported to have sticky surfaces that capture atmospheric dust particles (Harper & Belnap, 2001). If infiltration rates are decreased on BSC, runoff is generated that may wash dust particles and easily soluble compounds into an adjacent depression. An accumulation of salts and other elements may result. It is often cited that BSC may have this surface sealing property (Kidron *et al.*, 1999; Warren, 2001a). On the contrary, BSC may have better infiltration capacities than slight depressions when those are sealed due to a previous accumulation of clay and silt particles. Then, usually BSC-spots are leached over time, and only during strong rain events, surface runoff accumulates in slight depressions and leads to higher EC-values.

4.4.9 Variability Assessments on the Observatory

A description of the total variability of soil properties on the Observatory Soebatsfontein was critically to undertake: the appropriate statistical methods that make a coupled analysis of variance components across several hierarchical levels possible, require a data base with a regular structure, i.e. a hierarchical composition of units with the same number of subunits for each level of the superior unit. As the landscape subunits are not distributed regularly, this could not be achieved with the present data set, as was mentioned several times before (Chapter 2.4.1). This constraint was met in previous chapters by standardisation procedures and a combination of D2 and D3-units to a single factor "Site" for the ANOVA application.

However, at this point a first approach is made to evaluate the variability contribution of the observed D-units in total. For this purpose, the method of Square Sum Partitioning, a component of ANOVA, is modified (see chapter 2.4.1). For the modification, the model of a nested or hierarchical ANOVA is applied and calculated manually in Excel. Although this procedure vulnerates the postulation of a regularly structured data base, and is therefore not conductable with SPSS, it is accepted here since statistical tests are not needed at this point and the Square Sum Partitioning only fulfils the purpose of quantifying the variability between and within groups as a measure of explained and unexplained variability. Further, the present data set with its chosen unit system is regarded as an appropriate selection of all naturally occurring units to assess variability on the Soebatsfontein Observatory in a representative manner.

In Chapter 4.4.2.1 it could be shown that slope and mountaineous units differ strongly in terms of soil chemistry but also with regard to texture and inner structure in terms of D-unit organisation. Often, rocky outcrop units only vary on the D3-scale; on the D4-scale, BSC are widely missing or are at least not strongly developed. A differentiation on D4 was oftenly not possible since only Open Soil or only Plant Canopy-units occurred. This was partly due to the fact that in rock pockets and on small soil remnants on the smooth granite boulders, the whole soil was covered by plant crowns. In other cases, only Open Soil was sampled since plants were rare and very small, for instance in case of the Rock Fringe on the Mid-Eastern Slope (MS-RF).

Because of these basic differences the data base was divided into Rocky Outcrop and Slope data (with the Accumulation Zone data being grouped to Slope units) and variability partitioning calculated independendly for both. In Fig. 4.25, an overview is given for selected parameters on variance contribution of these overarching groups. The degree of variability explanation is rather low, with the exception of pH_{H2O}, whose variability is explained by 30% according to the conducted grouping.

For all variability analyses, six parameters were selected representing the main ecological influences. Those are pH_{H2O}, a property generally regarded as "master variable" citepMcBride:1994 for several soil properties, $EC_{2.5}$ as the representative for salt effects, C_{org} and N_t as measures of organic-dynamic properties and K_t and Ca_t as measures of texture, and secondary carbonate enrichment, respectively.

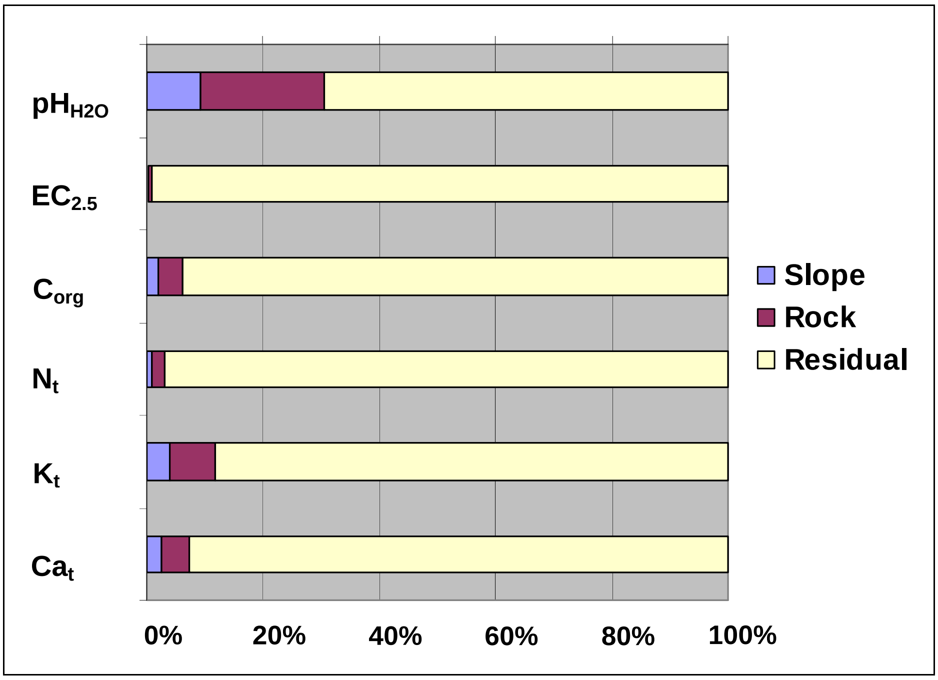

Fig. 4.25: Variability contribution of Rocky Outcrop- and Slope data on total variability on the Soebatsfontein Observatory.

The results for the "Slope" and "Rocky Outcrop"-group are provided in Fig 4.26. For the "Slope"-group, dominated by the occurrence of heuweltjies, the data shows that the four property groups react very differently. For pH_{H2O}, K_t and Ca_t, D3 contributes the most to overall variability. C_{org} and N_t show strikingly increased contributions of D4 and Layer on variability. Another group is represented by $EC_{2.5}$, the most dynamic parameter in the system. Here, D4-units hold the largest part of explained variance, but above that, residual or unexplained variability is largest amongst the tested parameters.

For the "Rocky Outcrop"-Group, different results are achieved. Ca_t, as an indicator for parent material, differs stronger from K_t by a higher contribution of D2, which is here a differentiation between Mountain Top (MT) and Mid-Eastern Slope (MS) unit. K_t is much more strongly controlled by D3-units. C_{org} and N_t-variability are strongly controlled by factor Layer, similar to the findings for the "Slope"-group.

A strong difference between the two groups occurs for $EC_{2.5}$. Here, D3 contributes much stronger to total variability than D4, as observed for the "Slope"-group.

4.4.10 Discussion of Variability Assessments on the Observatory

The analyis of variability fractionation within the total data set of Soebatsfontein revealed, that the differentiation into Rocky Outcrops and Slopes and therefore inherent

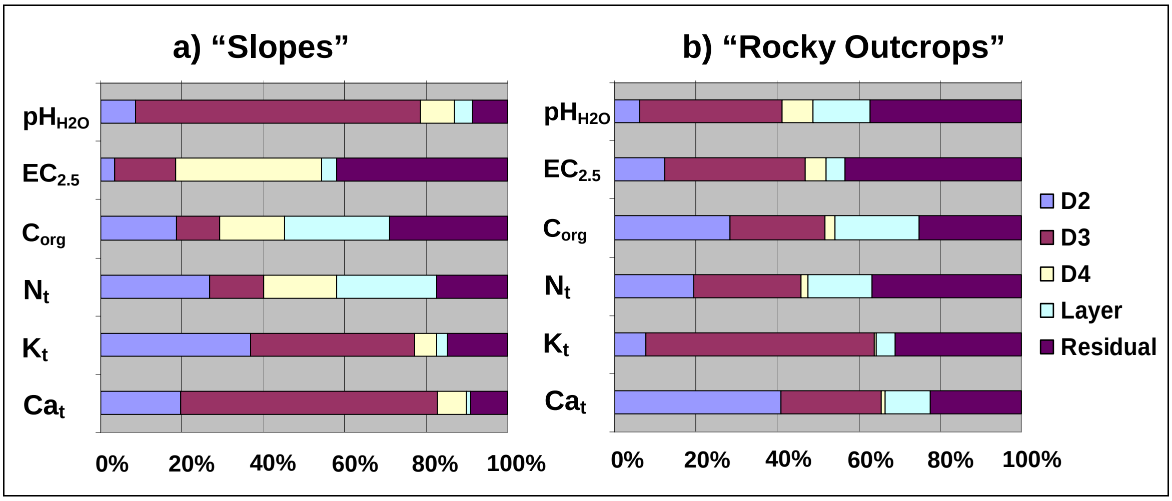

Fig. 4.26: Variability contribution of the hierarchical D-units on total variability on the Soebatsfontein Observatory. Left: on Slopes, Right: on Rocky-Outcrop Areas.

"D2"-units, have only little effect on the total varibility. This is valid for all parameters that were analysed with the exception of pH$_{H2O}$. The high contribution of the D3-units for the parameters pH$_{H2O}$, K$_t$ and Ca$_t$ in the "Slope"-group indicates the strong effect of heuweltjie/ interheuweltjie patterns on soils. As could be shown in Chapter 4.4.2.3 pH$_{H2O}$, K$_t$ and Ca$_t$ are exactly those properties strongly affected by heuweltjie/ matrix heterogeneity in the Slopes since heuweltjies on the one hand are characterised by higher silt contents in terms of texture and on the other by the accumulation of carbonates which also explains the effect on pH. For the "Rocky Outcrop" group, the findings differ strongly: since heuweltjies are missing, the variability fraction explained by D3-units is decreasing in favour of a higher contribution of residual variability. A similar trend is visible for Ca$_t$, although here a higher percentage is explained by D2, which is based on the differentiation into Mountain Top (MT) and Mid-Eastern Slope (MS) units. The D2 area "Mid-Eastern Slope" (MS) is adjacent to the other slope units and heuweltjies still occur in this area, though less frequently. Since heuweltjies act as a carbonate source on the entire, generally inclined flank of the mountain, the variability assessment results in higher D2 contributions. K$_t$, however, also strongly explains the variance on D3-units. When regarding Rocky Outcrops, several Matrix-units of different age and weathering and/ or erosional degree occur, which is connected to varying amounts of silt and clay contents. K$_t$ strongly correlates with the content of fine earth ($<$ 0.063 mm particle size); hence its variability contribution is so high in this unit although heuweltjie impact has to be excluded.

C$_{org}$ and N$_t$ are parameters especially connected with the distribution of shrubs but not with the occurrence of BSC, as could be shown in Chapter 4.4.3. Apart from a Plant Canopy/ Open Soil patterning, a gradient with depth could be verified, both reflected in examinations of the dwarf shrub effect on soil. Since Plant Canopy/ Open soil patterns are sampled in Rocky Outcrop and Slope units, the relatively high contribution of the factor "Layer" on total variability occurs in both groups. However, D4 contributes far less to Rocky Outcrop-units compared to Slopes. The reason for this is the stated lack of D4-differentiation on the D2 Mid-Eastern Slope (MS) and Mountain Top (MT). Here, the variability that a dwarf shrub exerts on the data base is not depicted in D4, but instead in D3, where a corresponding Open Soil unit was missing.

The variability of $EC_{2.5}$, is very strong in terms of "Layer" for the "Slope"-group, but with regard to D3-units for the "Rocky Outcrop" data set. The topsoil sampling depth contributes so much to overall variability on Slopes because of the properties of heuwelties having increased EC-values with depth. Also, the soils in the Slopes are loamy and develop a silty, several millimetres thick mineral soil crust on Open Soil patches. Therefore, the soils tend to be more stable and are more strongly differentiated within the first ten centimetres than the coarser soil between rock outcrops. Weathering of the rocks, run-off generation on the smooth boulder surface and the associated erosional forces lead to a stronger homogenisation of the topsoil in these areas. On the other hand, on a higher hierarchical level, namely D3, salt effects occur due to the patterning of Rock Fringe areas that receive primarily run-on, and lower lying Matrix-units that only participate in run-on/ run-off interactions when rain events are exceptionally strong. However, a second effect due to the lack of D4-differentiation as described above may not be excluded either.

Above that, in both groups residual or unexplained variability was largest for $EC_{2.5}$ among the tested parameters. In 4.4.7 the attempt to reduce the residual variability at least qualitatively by introducing another factor "microtopography" failed. It is assumed that too many factors on the smaller scale as observed interact on these dynamic properties, so that a further quantification is not achievable with the applied systematic sampling concept.

4.4.11 Hydrology

4.4.11.1 Topsoil Water Contents after Rain Events

The gravimetric water content (GWC) of samples taken directly after rain events had been calculated in mm water contents (see Chapter 2.2.5). This way, the water contents of the wetted depth are readily comparable to the amount of precipitation. Aim of this field test was to assess, whether different D4 and D3-units would lead to different water distribution and thus to a patchiness in terms of this resource.

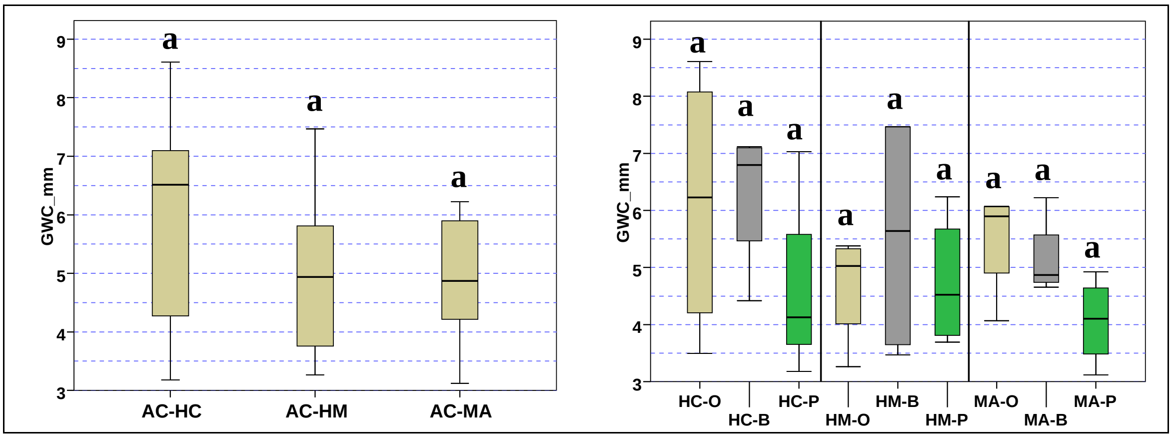

Fig. 4.27: Topsoil water contents (GWC) on D3- (left) and D4-scale (right) for the study site Accumulation Zone (AC) after a 6 mm rain event in the night from 20 - 21/08/2004. Coloured boxes on D4-scale indicate: brown: Open Soil; grey: BSC; green: Plant Canopy.

On the study site "Accumulation Zone" (AC)no significant differences could be obtained on the D3-scale between Heuweltjie-Centre (HC), Heuweltjie Margin (HM) and Matrix soil (MA) after a slight rain event of app. 6 mm (Fig. 4.27). On the D4-scale, those units were further subdivided into Open Soil, BSC and Plant Canopy (*Drosanthemum hispidium*). Here, no significant differences were determined either according to Mann-Whitney U test between D4-units of the same D3-unit, although the tendency of plant subunits with lower water contents within each group compared to other D4-units is clearly visible.

On the study site "Lower Eastern Slope" (ES), after a rain event of estimated 14 mm on August 26, 2005[5], differences are more pronounced (Fig. 4.28). Significantly more water had been stored on Heuweltjie-Center (HC) soils compared to the Margin (HM) and the Matrix-unit (MA1). However, although the mean shows a further decline on the Matrix-unit (MA1), no significant difference on the 0.05 level was found when applying the Mann-Whitney U test between Matrix (MA1) and Margin (HM)-unit. A different picture is obtained when examining the D4-scale. On the Heuweltjie-Center (HC) and on Heuweltjie-Margin (HM), decreased values on the plant related

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[5] according to BIOTA weatherdata the rain event only reached 5 mm on that day. However, this seems too low when regarding the GWC values.

units "Dead Shrub" (D) and "Plant Canopy" (P) compared to related Open Soil (O) and BSC-units (B) were obtained, although this was only tested significantly on the Heuweltjie-Margin.

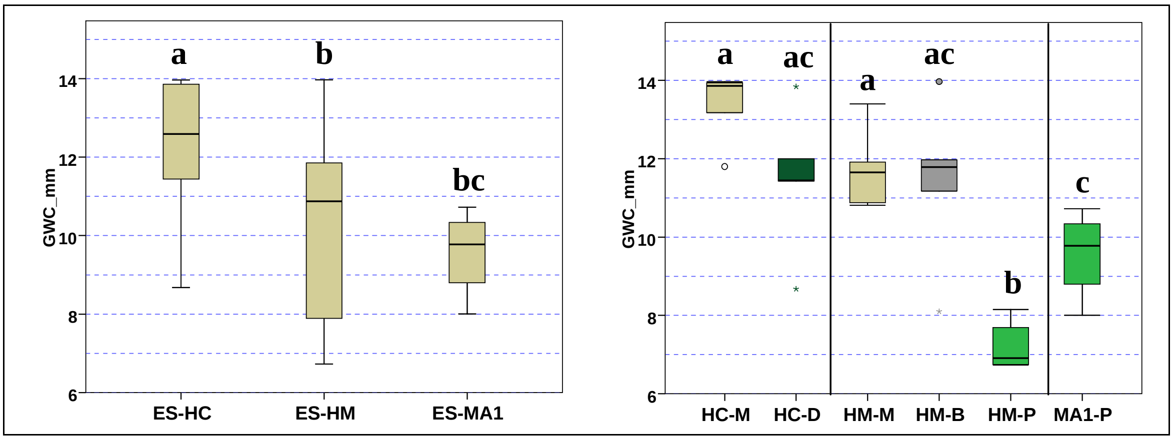

Fig. 4.28: Topsoil water contents (GWC) on D3- (left) and D4-scale (right) for the study site Lower Eastern Slope (ES) after 14 mm precipitation on 26/08/2005. Coloured boxes on D4-scale indicate: brown: Open Soil; grey: BSC; light green: Plant Canopy; dark green: Dead Shrub.

In the Matrix-unit at the foot of the heuweltjie (ES-MA1), the water content was significantly higher compared to the Plant Canopy-unit on the Heuweltjie-Margin (MA1-P). Unfortunately, no data is available for the Open Soil on the D3-Matrix unit, since the area was homogeneously covered with plants and unaffected patches were hardly found.

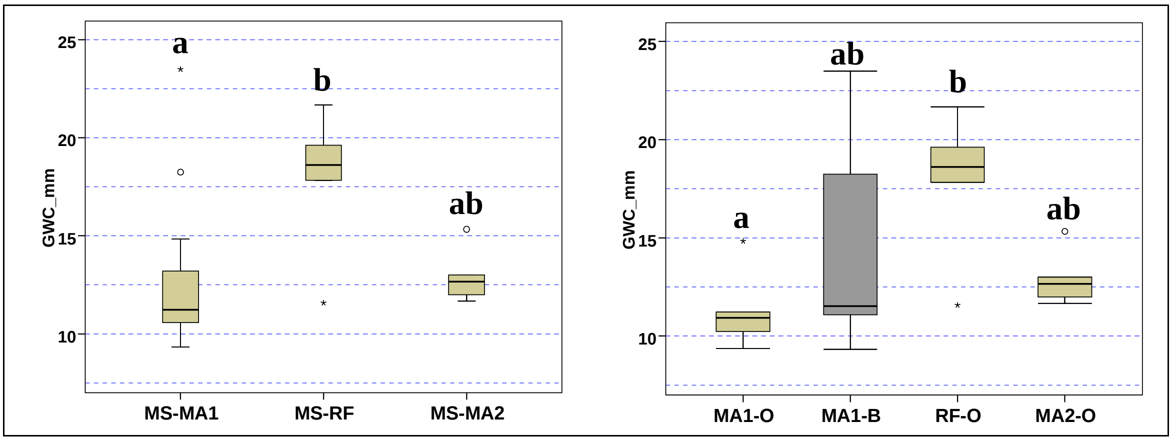

Fig. 4.29: Topsoil water contents (GWC) on D3- (left) and D4-scale (right) for the study site Mid-Eastern Slope (MS) after 14 mm precipitation on 26/08/2005. Coloured boxes on D4-scale indicate: brown: Open Soil; grey: BSC.

The Mid-Eastern Slope study site (MS) was sampled on the same day as the

Lower Eastern Slope study site (ES), after an estimated rain event of 14 mm (Fig. 4.29). Regarding the results on the D3-level, only the Rock Fringe (RF) and the Upper Matrix-unit(MA1) are significantly different. Nevertheless, there is also a strong tendency of increased water content compared to the Lower Matrix (MA2). On the D4-level, only one further focus is possible: the Upper Matrix is subdivided into Open Soil (MA1-O) and BSC-units (MA1-B). The BSC accounts for most of the variability.

Further GWC-samples were taken on the Western Slope D3-unit "Matrix" (WS-MA) after a rain event of 19 mm on October 17, 2005 (Fig. 4.30). Samples were taken on the D4 units Open Soil (WS-MA-O), BSC (WS-MA-B) and Plant Canopy (WS-MA-P). A significant difference becomes apparent when comparing the Open soil and the BSC-unit, with soils on Open Soil-units having stored less water than on BSC and Plant Canopy-units.

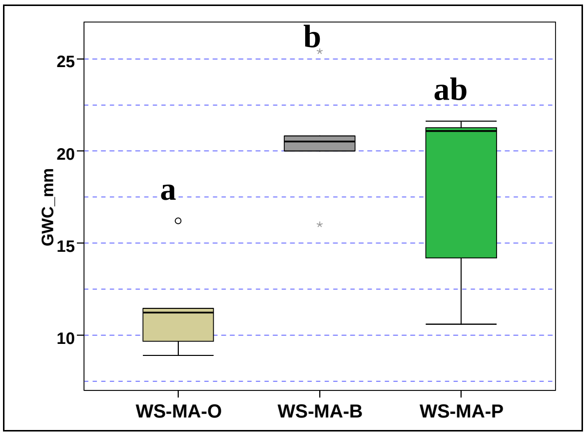

Fig. 4.30: Topsoil water contents (GWC) on D4-scale for the study site Western Slope (WS) after a rain event of 19 mm on 17/10/2005. Coloured boxes on D4-scale indicate: brown: Open Soil; grey: BSC; green: Plant Canopy.

4.4.11.2 Infiltration Rates

Infiltration Rates were measured on D3-units of the study sites Accumulation Zone (AC), Mid-Eastern Slope (MS), Mountain Top (MT) and the heuweltjie-site on the Lower Eastern Slope (ES). It was not always possible to differentiate on the D4-level (see Chapter 2.2.6); however, it was assumed that BSC might have a major influence on infiltation rate, thus, additional tests were applied on exceptionally well developed BSC sites a little outside of the northern margin of the observatory. For this test, the infiltration rings were fixed on the BSC, the test conducted and then repeated after several hours time. Fig. 4.31 shows boxplots created for all D3-units and the BSC-tests.

The infiltration rates vary widely on the whole data set with lowest values of 16 mm/h and highest values of 4,850 mm/h. Lowest infiltration rates occur on the BSC-test sites as well as Heuweltjie-Centre (AC-HC) and Margins (AC-HM) of the Accumulation Zone and the Heuweltjie Centre (ES-HC), Matrix1 (ES-MA1: Heuweltjie basis) and Matrix2 (ES-MA2: Quartz Field) of the Lower Eastern Slope-site. Highest values were measured on the Mid-Eastern Slopes' Rock Fringe (MS-RF) and the Heuweltjie Margin of the Lower Eastern Slope (ES-HM). Regarding all tests in summary, the median is at 192 mm/h and the mean at 370 mm/h.

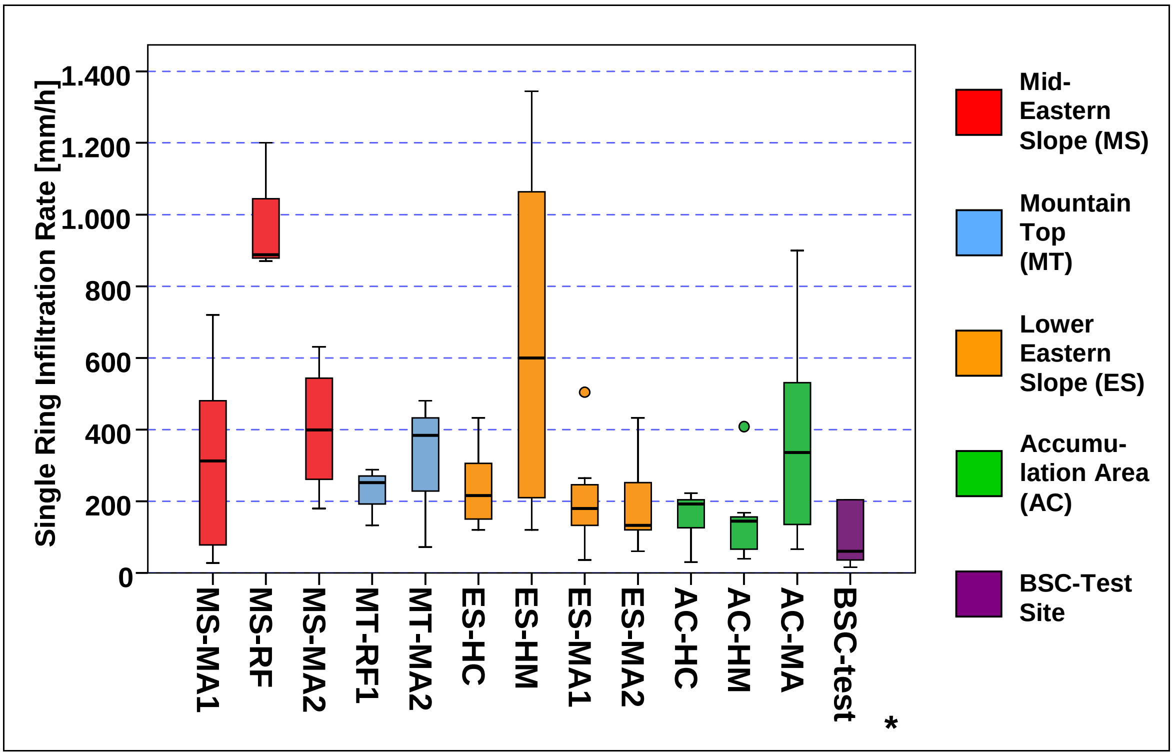

Fig. 4.31: Single ring infiltration rates on all tested D3-units in comparison (∗: two not-depicted outliers of BSC-test at 3,400 and 4,800 mm/h).

When regarding the infiltration rates for D3-units on the Mid-Eastern Slope (MS) (Fig. 4.32), significantly higher infiltration rates were determined on the Rock Fringe (RF) in comparison to the Upper and the Lower Matrix areas (MA1 and MA2) that were not tested significantly different on 0.05 level. However, a different view is achieved if distinguishing on the D4-level: if tests of the Upper Matrix area MS-MA1 are split with regard to occurrence of BSC or not, results show significant differences between those groups with BSC-units featuring the lowest infiltration rates. Due to both, occurrence of BSC lowering IR and Rock Fringes increasing it, this study site shows the highest variability of IR.

On other study sites, however, no such big differences occur. On the study site Lower Eastern Slope (ES) (Fig. 4.33), on D3-units the only difference on 0.05 level was tested between the Heuweltjie-Center (ES-HC) and the Matrix2-unit (ES-MA2), two units that are quite different in genesis (heuweltjie-origin and quartz debris as

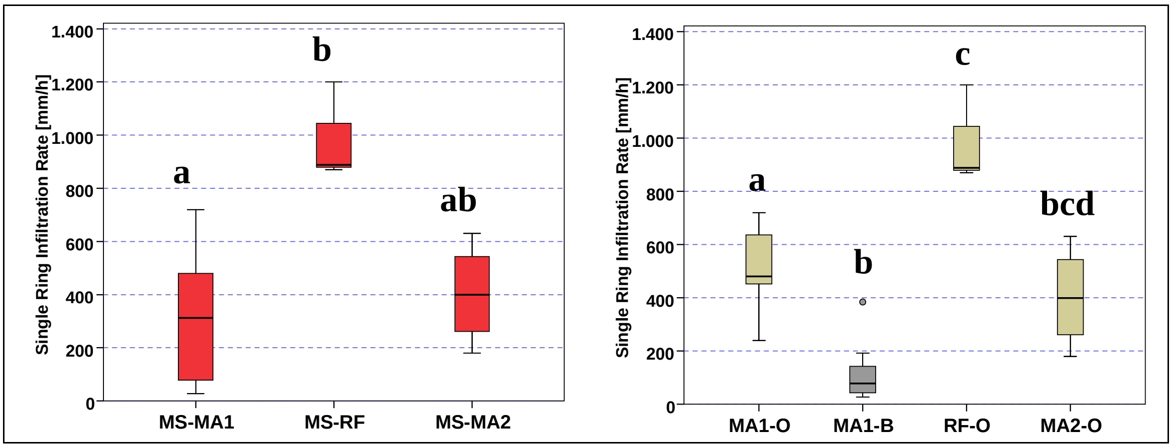

Fig. 4.32: Single ring infiltration rates on D3 and D4-scale on the study site Mid-Eastern Slope (MS). Coloured boxes on D4-scale indicate: brown: Open Soil; grey: BSC.

parent material, respectively). The different heuweltjie-units were not tested different by the Mann-Whitney U test. It only appears that variability is strongly increased on Heuweltjie-Margin sites (HM) than on others. The same results are achieved when applying the significance test on D4-scale: only differences according to Mann-Whitney U test occur between the two quartz pebble units and the Heuweltjie Margin.

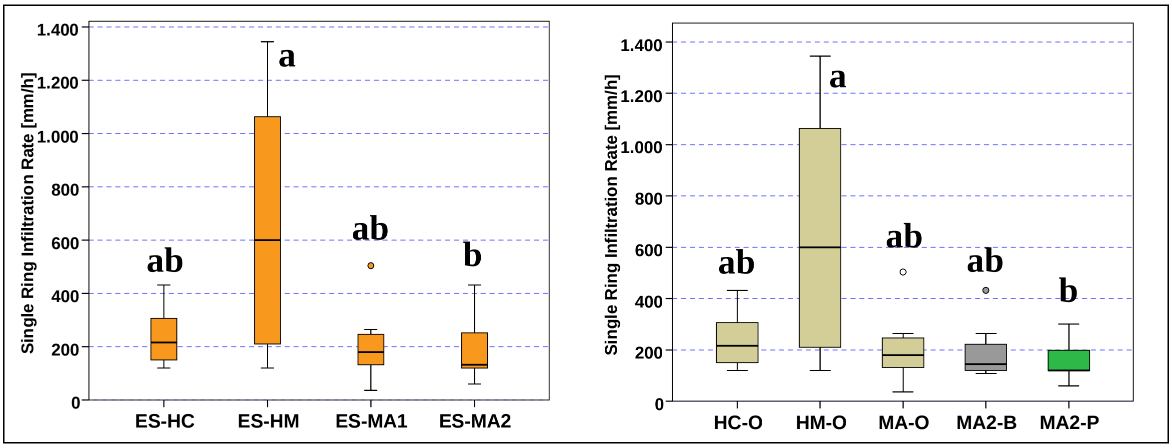

Fig. 4.33: Single ring infiltration rates on D3 and D4-scale on the study site Lower Eastern Slope (ES). Coloured boxes on D4-scale indicate: brown: Open Soil; grey: BSC; green: Plant Canopy.

A rather special situation was found on the last study site, the Accumulation Zone (AC) (Fig. 4.34). On the Heuweltjie-Centre (HC), Margin (HM) and the Matrix soil at the foot of the heuweltjie (MA), infiltration rates were conducted on microsites that were determined as Open Soil and BSC units. When regarding the results on the D3-

scale, no significant differences were tested between the three units. However, it was striking that on the Matrix unit (MA), variability was exceptionally high compared to the other two units. On the D4-scale, another pattern occurred: originally, the Matrix-unit was not separately tested for BSC and Open Soil on D4, since BSC did not occur very distinctly. On the other two, a differentiation between Open Soil and BSC was conducted but resulted in no significant difference on the 0.05 level when applying the Mann-Whitney U test. Therefore, the high variability of the Matrix-unit continued to be striking and the descriptions that were carried out for each micro-testsite were regarded a bit more closely; according to the description, the Open Soil was divided into two subunits: into the actual "Open Soil" that was characterised by a soft physical crust on this D3-unit, renamed into "Mineral Crust" (MC), and sites on which the crust was covered with coarse sand particles (S). When regarding these two as different D4-units, the slightly crusted Open Soil (AC-MA-MC) grouped to the other D4-units on the Heuweltjie-Margin and Centre; the Coarse Sand covered test plots (AC-MA-S), however, showed clearly increased infiltration rates compared to the other units. Due to the low sample size of n=3, this finding could not be confirmed on $p<0.05$ significance level, although this decision was close ($p=0.057$). After examining the test descriptions for the other D3-units on the Accumulation Zone as well, the Open Soil unit of the Margin turned out to also be characterised by Coarse Sand coverage. Here, an increasing effect of the Coarse Sand on the infiltration rate is also visible, albeit not significant.

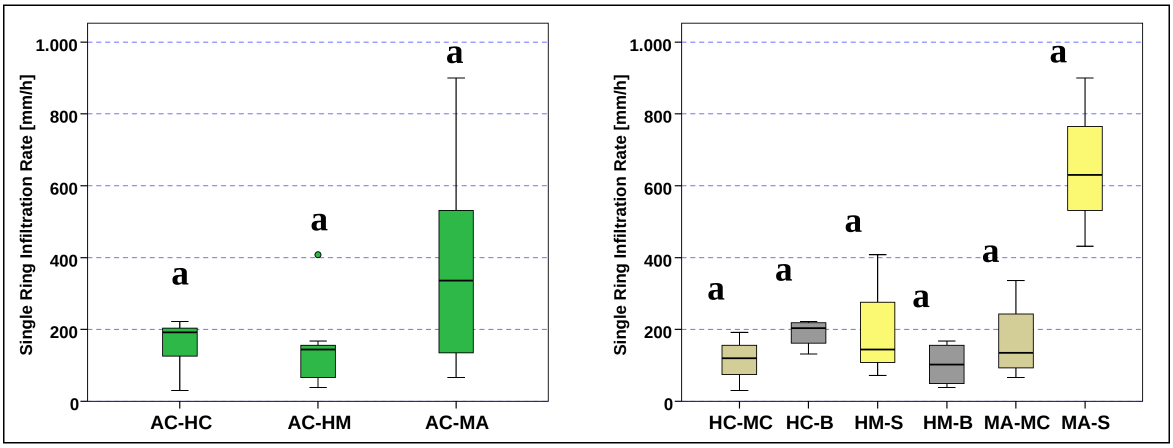

Fig. 4.34: Single ring infiltration rates on D3 and D4-scale on the study site Accumulation Zone (AC). D4-units were slightly changed compared to the primarily defined structures (Explanations see text). Coloured boxes on D4-scale indicate: brown: Mineral Crust; grey: BSC; yellow: Coarse Sand Cover.

4.4.12 Discussion of Hydrology

A comparison between gravimetric water contents and infiltration rates was not possible everywhere since infiltration rates could not always be taken on the D4 but only on the D3-scale (see Chapter 2.2). Also, measuring infiltration rates below plant canopies on the Lower Eastern Slope-study site was not possible as shrubs were too small to fix the infiltration ring below their canopy and too large to impose the ring over the whole plant.

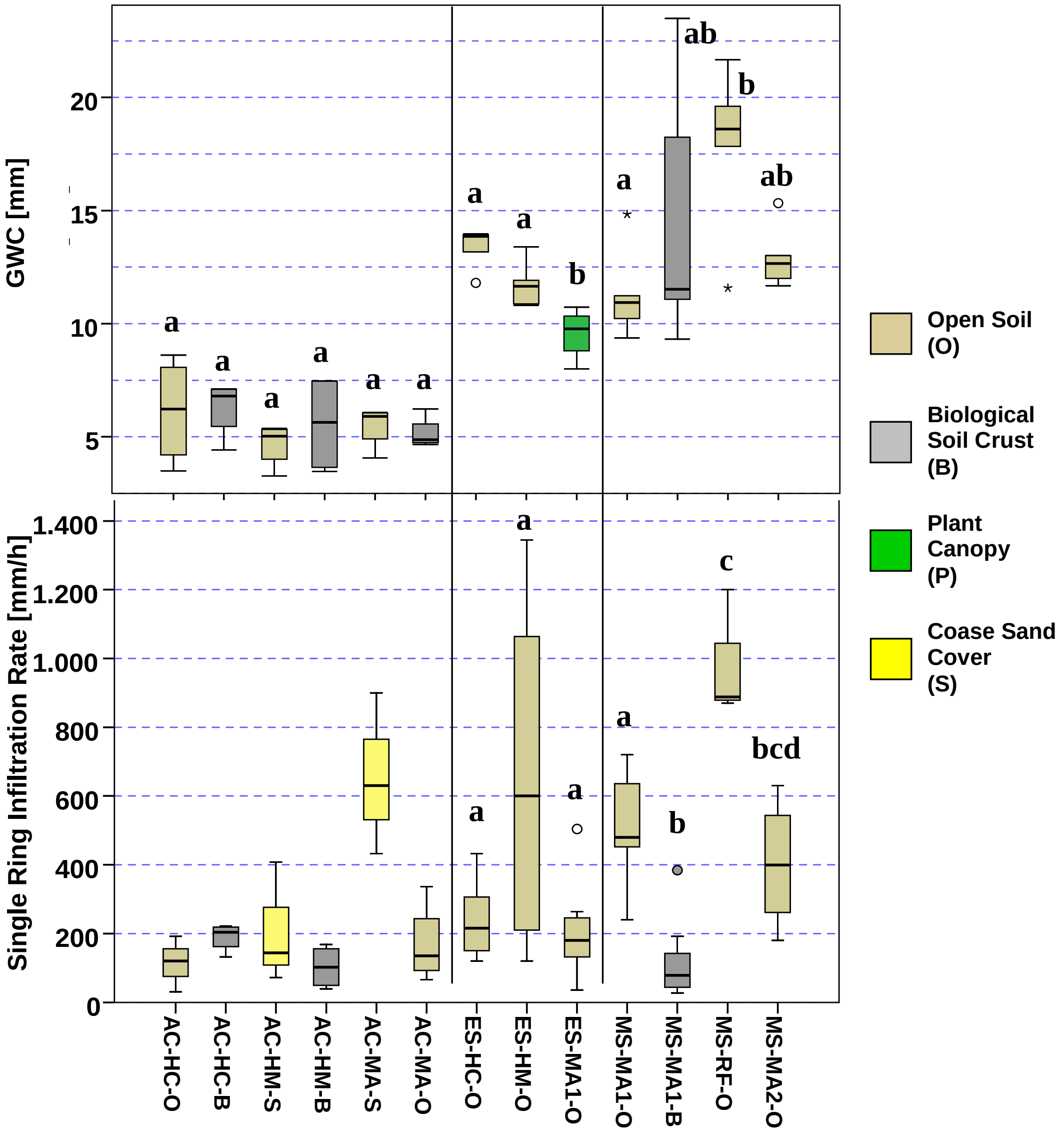

Fig. 4.35: Comparison of topsoil water content measurements and single ring infiltration rates on all sites where comparable data sets were available. Where significance tests are missing, the sample size was below n = 5.

However, main tendencies of infiltration tests and gravimetric water contents were in accordance with each other (Fig. 4.35). Following a 6 mm rain event on the Accumulation Zone (AC), no significant differences could be determined between all units with regard to gravimetric water contents. The infiltration rates, mean values ranging between 102 mm/h (AC-HM-B) and 986 mm/h (MS-RF-M), showed slight differences between most D4-units and high values on the newly defined group AC-MA-S. The reason for the different pattern of infiltration rate and water contents can be attributed to the fact that the rainfall preceding the sampling was very low; though rain events of this size are not untypical for the winter rainfall area, differences between the units might be less pronounced compared to stronger rain events. However, it is also possible, that small patches of coarse sand cover with their increased infiltration rates are sufficient to produce a relative homogeneous water distribution on the whole interheuweltjie site beyond the borders of this only several decimeter sized D4-unit. This would explain the slight difference in infiltration rates and the contrasting homogenous water distribution in the topsoil. However, no evidence is supporting this hypothesis when looking at current data and a second sampling after a stronger rain event is recommended.

On the Lower Eastern Slope study site (ES), gravimetric water contents showed significant differences on the 0.05 level between the unit at the heuweltjie foot (ES-MA1) and the two other units Heuweltjie-Centre (ES-HC) and Margin (ES-HM), which were tested as not significantly different. By means of statistical parameters such as mean, 25 and 75 percentile, the water content tended to decline from top to bottom of the heuweltjie, probably a texture effect or an effect of the lee-position of the heuweltjie transect. For infiltration rates, no significant differences were obtained on the D4-scale, which marks a difference to the comparable gravimetric water contents, as well as the fact that infiltration rates on the Heuweltjie-Margin were highly variable. However, this might be related to the same process that had been suggested for the coarse sand cover sites on Matrix soils on the Accumulation Zone (AC-MA): Patterns of high- and low infiltration patches may lead to a rather homogenous water distribution when these patches alternate on a small scale. As Ludwig *et al.* (2000) suggest, the scale of these patches may increase as a consequence of degradation processes that involve crusting and compaction. Thus, larger patches of low infiltration may develop, leading to more run-off generation during heavy rain falls and subsequently to an increased erosive force. However, particularly the redistribution of the vital resource water becomes less effective in this case. Conclusively, the results for Soebatsfontein indicate that *in sensu* Ludwig *et al.* (2000) the landscape still acts in the state of resource conserving rather than a "leaky" or "dystroph" landscape since patches alternate on a small scale and a homogenous water distribution is present. On the other hand, it has to be considered whether the hypotheses of Ludwig *et al.* (2000), which were developed for savannas and alternating patches of vegetation (= high infiltration) and bare soil (= low infiltration), are fully applicable to the Succulent Karoo ecosystem as well.

Of further interest was the finding that Dead Shrub and Plant Canopies-units on this site stored less water after a rain event than Open Soil and BSC-units. This might be interpreted in such a way that canopies of plants, even a certain time period after their death, either shield rain drops, thus leading to less water directly below canopies, or, in terms of living plants, readily use up the additional water after rain. In principle, plants of semi-arid environments were reported to follow different strategies to "harvest" rain water. These are based on *stemflow*, *throughfall* and *canopy storage*. When rain begins to fall, the drops partly encounter the leaves and branches of a plant. Thus,a certain amount of water adheres to the crown, making up the *canopy storage* or *interception*. This part of the water easily evaporates once the rain has ceased. The volume of water lost by evaporation from the wetted canopy is the *canopy interception loss*. Depending on the intensity of rain, the water storing capacity of the crown is exceeded and water drops gather and either begin trickling downwards or follow leaves and branches until they reach the stem and accumulate to the so-called *stemflow*. However, depending on the density of the plant, a certain amount of rain drops will fall through the canopy and directly infiltrates into the soil (Dunkerley, 2000b). Domingo *et al.* (1998) observed the effect of three different canopy structures of two semi-arid shrubs and a tussock grass on rainfall partitioning. One strategy was to invest resources into an extensive root system that is able to exploit deep water resources. These shrubs had very open canopies. A second strategy type had an intermediate root system but invested into an optimisation of its canopy structure in a way, that leaves and branches acted as funnels, therefore draining a high proportion of rainfall as stemflow. The last plant species, a tussock grass, was characterised by shallow root systems and dead plant leaves as a continued part of the plant, leading to high canopy storage capacity and consequently high interception losses. However, Domingo *et al.* (1998) interprete this seeming disadvantage as a strategy leading to higher efficiency in using top soil water and in capturing water and sediments.

The lower water contents below Plant Canopies-units in Soebatsfontein may be due to a sampling within canopy areas of a plant, that follows the strategy of harvesting water by stemflow generation. This assumed, it may be possible that the sampling of topsoil after rain events with 4 cm-diameter core samplers may have simply been beyond the accumulation zone. A rapid intake of this resource and subsequent storage within the leaves of the succulents may be another thought to follow. Additionally, it has to be considered that the intensity of precipitation may have not been sufficient to exceed a threshold of stemflow generation. All these hypotheses have further to be investigated within the context of topography; the water content in the Matrix-unit at the foot of the Lower Eastern Slope-heuweltjie (ES-MA-P) was significantly higher compared to the Plant Canopy-unit on the Heuweltjie-Margin (ES-HM-P), probably due to accumulation in this edge position (compare Fig. 4.28).

The strongest accordance of the two hydrology tests were obtained on the Mid-Eastern Slope site (MS). The Rock Fringe unit (MS-RF) has the highest infiltration rates and gravimetric water contents compared to the other units. On the other hand, the data deviates in terms of the D3-unit "Upper Matrix" (MS-MA1) that is subdivided on D4-scale into Open Soil (O) and BSC (B). While gravimetric water contents for the Open Soil data is lower and the BSC exhibits a strong variability within the data, infiltration rates show rather the opposite trend with Open Soil having significantly featuring values than adjacent BSC-patches. Since the soil on the upper Matrix (MS-MA1) is quite shallow and the whole study site is considerably inclined, it becomes clear again that not only the in-situ infiltration rate controls the distribution of water but also the patchiness of infiltration rates in the surrounding and - in this case - upslope areas.

For the site Western Slope Matrix (WS-MA), no infiltration data exists for a comparison with the gravimetric water contents. The latter, however, showed interesting results with BSC (B) and Plant Canopy (P) soils having higher water contents than the Open Soil (O)-unit although topographically, BSC and Plant Canopy areas are situated on more strongly inclined areas, while the Open Soil unit on this site was more strongly levelled. However, it was assumed earlier that the Open Soil unit is affected by erosion: the Open Soil areas may have been developed out of so-called ”voetpaadjies”, sheep and goat trails emanating from the formerly stockpost nearby. Under influence of several rain events, these stripes broadened, levelled and became subject to slaking, compaction and consequently crust formation. This hypothesis applies to the obtained gravimetric water content results: although BSC and Plant Canopy areas are more inclined, they exhibit higher water contents, probably because of better infiltration capacities of the rougher surface and the less crusted canopy areas of dwarf shrubs. On the planar bare soil, infiltration is low as a consequence of the degradation processes such as compaction. On the other hand, water ponds on these areas after rain events readily evaporate and leave dissolved salts behind, leading over time to the observed accumulation of salts, which is reflected for instance by the high EC-values (compare Chapter 4.4.7.3). This effect may be enhanced by a leaching effect of the inclined areas, so that a redistribution of nutrients takes place from inclined to planar units.

In conclusion, varying factors control the water content of topsoils after rain events: those are

1. climatic factors such as rain intensity, and - as was assumed for lee- or luvward exposition of a heuweltjie - wind intensity and direction
2. structural factors such as slope, roughness or canopy habitus
3. soil factors influencing the infiltration rate such as amount of clogging particles (esp. silt) (Mills & Fey, 2004a), soil structure, biopores and biological soil crusts.

It can further be stated that infiltration rates obtained for Soebatsfontein are highly variable which corresponds to the above stated diagnosis that infiltration rate is a function of multiple interacting soil factors. In some cases, the values are very high with infiltration rates > 800 mm/h, for instance within the Rock Fringe area (RF). These were previously assumed to have ecological significance in water harvesting and pattern development, which contributes to the high diversity observed in Soebatsfontein in terms of both, soil properties and biological diversity (Petersen, 2008). Further, the increased infiltration rate of patches with coarse sand cover indicates a possible ecological role *in sensu* Ludwig *et al.* (2000) and related studies (see Chapter 3.2). The effect of dwarf shrub crowns on water redistribution remains largely unclear; although data indicates interception losses, an accumulation of water via stemflow is not excluded. All in all, the collected hydrological data is not sufficient in sample size to clearly identify and statistically confirm processes controlling rain water distribution. Nevertheless, the findings show first trends that are worth supplementing with further field measurements.

5 Comparison of Scale Dependent Topsoil Variability in two different Landuse Systems in the Nama Karoo Ecosystem

5.1 Introduction

The BIOTA twin-observatories 10 Gellap Ost and 11 Nabaos are located in the Karas Region of Southern Namibia, approx. 15 km NW of the town Keetmanshoop. Geographically, the area belongs to the Nama-Karoo biome, which is characterised by a summer rainfall regime ranging from 100 to 150 mm annual precipitation. The predominant vegetation type is dwarf shrub savanna.

The observatories more or less directly abut one another and are subject to different land use systems: the Nabaos Observatory is located on the Tyrvlei, which belongs to the communal land of the Nama that vastly extends to the North. In the 1970s, landuse changed from formerly commercial to communal land. As such, the area is managed as open access rangeland. The adjacent Gellap Ost Observatory belongs to the Governmental Research Station Gellap Ost that covers a total area of 13,734 hectares. The farm is commercially managed with low stocking densities and fenced into camps; here, a rotational grazing system is applied which allots resting periods to the camps. The difference in landuse is clearly expressed by a striking fenceline contrast along the boundary between the twin observatories (Fig. 5.1): while on Gellap Ost, the veld is in a good state and characterised by shrubs and perennial grasses alike, the Nabaos rangeland is clearly degraded. Palatable grasses are absent, however, after rainfall innumerable annuals emerge and provide livestock with protein-rich fodder, which is commonly termed as ”Opslag” (Afrikaans: supplement).

Topographically, the area is ranging in altitude from to 1044 to 1105 in Nabaos and from 1097 to 1164 m asl in Gellap, respectively. Dominant morphological units are by 4-5% westerly inclined plains, shale outcrops and rivier[6]. It has to be noted that Nabaos is influenced by a larger catchment in the eastern surrounding area, which causes a stronger drainage structure in the observatory (Petersen, 2008). This finding is to be considered when comparing data of the two observatories.

The Nama Karoo is a vast biome and, according to Palmer & Hoffman (2004), not much is known about its ecology. However, against the background of its significance as a rangeland and livelihood for subsistence and commercial farmers alike, a better understanding of the ecosystem, especially with regard to anthropogenic influence, seems crucial. Moreover, global warming and the suggested shift of ecosystem boundaries with increasing desertification tendencies underline this aim. Therefore, the BIOTA observatories in the Nama Karoo were chosen to conduct studies on topsoil variability with regard to a nested scale system as in Soebatsfontein. Special focus is placed on the landuse impact.

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[6] the Afrikaans word rivier indicates a dry riverbed that only carries water after rainfalls

The following key questions shall be solved:

- how variable are topsoil properties on the two observatories?
- is variability comparable on Gellap and Nabaos?
- are their significant differences in soil properties between microfeatures?
- to which extent does microtopography contribute to variability?
- to which extent do patterns and scales contribute to overall variability of topsoils on the observatories?

Fig. 5.1: Fenceline contrast between the observatories Gellap (left) and Nabaos (right)

5.2 Characterisation of the Study Site

5.2.1 Geology and Geomorphology

The present study area is situated somewhat North of the formerly mentioned Namaqualand Metamorphic Province, which builds up the basic bedrock of Namaqualand and has its northernmost outcrops in the Karasberge, South of Keetmanshoop (compare Fig. 4.1). Additionally, the rocks of the Namaqualand Metamorphic Province, together with the quartzites, shists and limestones of the Nama groups, form the underlying bedrock of the study site. The uppermost sediments forming the geologic parent material of the soils in Gellap and Nabaos belong to the so-called Karoo Supergroup, whose genesis dates back to 300 - 180 Ma before present.

During the Gondwana-Ice-Age (300 to 280 Ma bp), vast parts of Namibia were covered with glaciers. After the ice masses were molten, massiv layers of morain materials remained on the surface, which are now forming the Dwyka-formation of the Karoo Sequence. These glacial deposits are the basic sediments of the following warmer and moister Karoo-Age during which shallow lakes and swamps developed. These filled with clayey-sandy sediments and were in subsequent ages transformed to grey shists that build up the main parent material of soil in the study area. These belong to the Prince-Albert formation of the Ecca group (Genis & Schalk, 1994; Gerschütz, 1997).

Although not occurring on the twin observatories, a dominant geologic feature of the surrounding area shall be introduced: dolerites form sills and dykes in the landscape, which intruded the sedimentary successions to the north and north-east of Keetmanshoop. A more detailed description of the geology is found in Grünert (2005).

Geomorphologically, the observatories are characterised by large plains and slightly inclined washes or glacis structures. Predominant features within these plains are "inselbergs"[7] of the shales that typically have a conelike shape (Petersen, 2008). Some of them, for instance a mountain occurring on the Gellap Observatory, have a plateau due to harder layers within the shales that are more strongly resistant to erosion processes.

5.2.2 Climate

The Nama Karoo receives predominantly summer rainfall in the months December to March (Palmer & Hoffman, 2004). This kind of precipitation differs in character from the light, low erosive and highly predictable winter rainfalls of the westerly adjoining Succulent Karoo. The rainfall is highly erratic, occurs often as locally restricted thunderstorms and frequently exhibits a strong erosive force. Annual mean precipitation ranges for the Nama Karoo between 60 and 400 mm (Palmer & Hoffman, 2004), and for the surrounding of Keetmanshoop between 100 and 150 mm (Mendelsohn *et al.*, 2002). However, data of the BIOTA weather station, which is directly located between

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[7] single mountain or a group of mountains that rise like islands out of vast plains. Frequent are remnants of the formerly land surface that has vastly eroded away.

the observatories Nabaos and Gellap, show a slightly different trend: the rainy season is between January and April and the mean annual rainfall, calculated for data of the years 2002 to 2006, amounts to a mean of approx. 180 mm. However, this is due to the rather short measurement period that involves the very good rainfall in 2005 (205 mm) and 2006 (320 mm) (see Fig. 5.2).

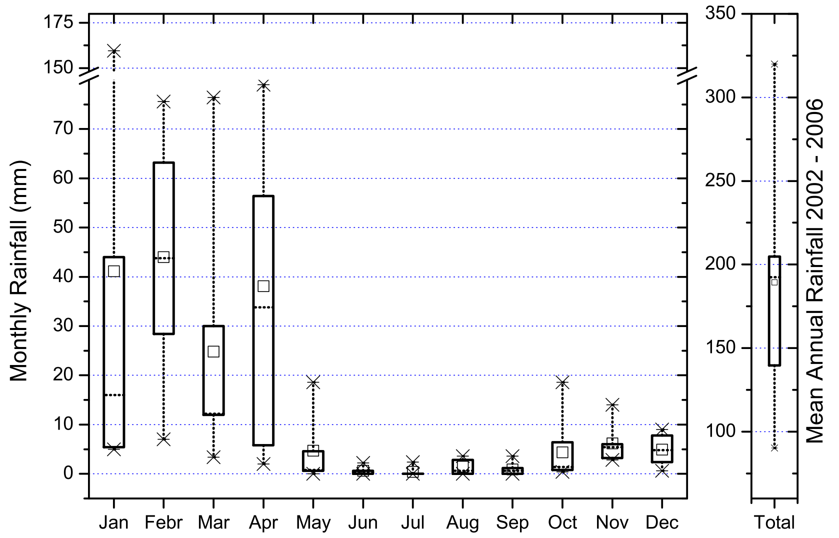


Fig. 5.2: Monthly rainfall from Aug 2001 - Oct 2007 and total rainfall from 2002 - 2006 at the BIOTA observatories Gellap and Nabaos (Source: www.biota-africa.org).

Temperature fluctuation is quite pronounced in this environment: in June, the coldest winter month, mean daily temperatures reach approx. 15°C, while lowest and highest daily temperatures range between -0.5 and 29°. 5 to 10 days of frost several degrees below zero are common. In summer, with its hottest month January, mean daily temperatures reach approx. 27°C with lowest and highest daily temperatures ranging between 11 and 43°C (see Fig 5.3). Relative humidity ranges from 10 to 20% to a max of 30 - 40% in the most humid month (Mendelsohn *et al.*, 2002).

The amount of rainfall may be a critical factor for plant growth for an ecosystem, especially when it is used for agricultural purposes. But, additionally its reliability is of importance. The reliability of rainfall can for instance be described by the coefficient of variation (CV), which is the standard deviation of annual totals as a percentage of average annual rainfall. For the Keetmanshoop surroundings, this CV is ranging between 60 and 80% for the study sites which means that rainfall is quite unreliable. In comparison, the CV of Namaqualand reaches approx. 33-37% (Cowling & Hilton-Taylor, 1999b). Apart from rainfall and its distribution patterns, a third main factor affects the availability of water in the soil: the evaporation rate. According to Mendelsohn *et al.* (2002), in Keetmanshoop and the surrounding areas, average annual evaporation reaches more than 2,660 mm/year. This results in a climatic water deficit of 2,300 - 2,500 mm/year for this area. Lookint at this data it becomes very clear that water

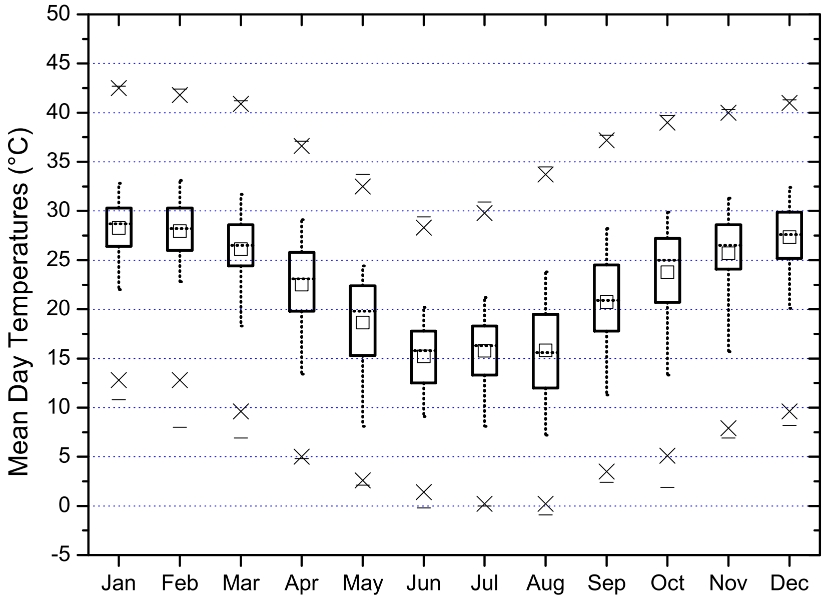


Fig. 5.3: Mean, maximum and minimum daily temperatures at the BIOTA observatories Gellap and Nabaos from Aug 2002 - Oct 2006 (Source: www.biota-africa.org).

availability is the most crucial factor influencing plant growth and ecosystem resilience and that these rangelands are most sensible to inadequate land management.

5.2.3 Vegetation

The study area belongs to the Nama Karoo biome, which covers an area of 607,235 km^2 and thus 22.7% of the total territory of southern Africa (Rutherford, 2004). The Nama Karoo borders on the Succulent Karoo to the West, the desert ecosystems in the North, on savannas and grasslands in the East, and on fynbos and savanna biomes in the South (Palmer & Hoffman, 2004).

Palmer & Hoffman (2004) further subdivide the Nama Karoo into three geographically distinct regions with regard to the tabulation of elevation and annual rainfall. According to these authors, the present study site belongs to the subdivision "Griqualand West and Bushmanland" with arid shrubland and arid grassland as the typical vegetation forms.

A detailed analysis of the vegetation of the twin observatories is found in Wolkenhauer (2003). In total, 126 species were found in the study areas that included the BIOTA observatories, with 12 species belonging to the family of Fabaceae, 11 to the Poaceae, 10 to the Aizoacea and 9 to the Asteraceae. Most abundant species were the phanerophytes *Boscia foetida* (Capparaceae), *Acacia nebrownii* (Mimosaceae) and *Acacia mellifera* (Mimosaceae), the Chamaephyte *Calicorema capitata* (Amaranthaceae) and the nanophanerophyte *Rhigozum trichotomum* (Bignoniaceae).

Further, Wolkenhauer (2003) states some botanical differences between the two observatories which are referred to the different landuse types. These comprise:

- a higher species diversity on Gellap with a contribution of 102 and 81% of the total species, respectively compared to Nabaos, where only 71 species (56% of the total number) were mapped.
- a greater coverage on Gellap by a factor of 2.4
- a stronger abundance of annual plants on Nabaos and a decreased number of palatable chamaephytes

Wolkenhauer (2003) also showed that the economically most important species *Stipagrostis uniplumis* (Poaceae) in Gellap Ost and *Tetragonia schenkii* (Aizoaceae) in Nabaos are mutually exclusive since *S. uniplumis* cannot establish due to the high grazing pressure in Nabaos and *T. schenkii* does not find suitable growth conditions because of its low competitive strength over grasses for water resources.

5.2.4 Landuse History and Utilisation

The history of agricultural use in the study area is approximately 2000 years old (Smith, 1999). Before that time, non-sedentary hunter-gatherers wandered through the Nama Karoo, but then the Khoikhoi established a form of pastoralism with a game hunting component in the region (Kempf, 1997). According to Kempf (1994), citet in Wolkenhauer (2003), approx. 1500 years ago cattle were introduced in the region by nomads, who changed with their herds periodically between rangelands in the summer rain receiving Nama Karoo and the winter rainfall realm of the Sukkulent Karoo. Wolkenhauer (2003) summarises the further development of landuse history:

At the beginning of the twentieth century, colonialisation led to the immigration of German settlers. The aboriginal semi-nomadic Nama population was expropriated, sedentarised and relocated into "temporary reservations". A change occurred during the 1960s, when the Odendaal plan led to an extension and reorganisation of the reservations. The reservations of Keetmanshoop, Gibeon and Bethanien were merged into one and supplemented with adjacent white farmland. This way, the Communal Area Namaland was established and consequently administrated by tribe councils. Since Namibias independence in 1990, the area belongs to the districts Hardap and Karas.

The southern region of Namibia is sparsely populated with a density of only 0.73 people per km^2 (Kuiper & Meadows, 2002). The area accounts for approximately 5% of the national population of 1.6 million. The land tenure system is divided into communal and commercial lands; according to Klintenberg & Seely (2004) the communal land is owned by the government and can be used by anyone but withough exclusive rights. In 1999, 41% of Namibia was communal land (Wolkenhauer, 2003). By contrast, the commercial freehold land is owned by individuals who hold exclusive rights.

Predominant agricultural export products of southern Namibia are meat and - until the 1980s of high but nowadays of lower importance - Karakul skin (Jürgens & Bähr, 2002). Dorper and Damara sheep are held for meat production although their impact on the fragile ecosystem is regarded as critical compared to Karakul. A lactating ewe needs a lot of fodder when a lamb should reach its slaughter weight of 18 to 20 kg which can result in overgrazing in times of drought if the herdsize is not diminished; concerning the Karakul, however, the lambs are slaughtered within 48 hours after birth. Therefore, an additional fodder requirement is not given (Grotehusmann, 2006).

70% of the Namibians depend on subsistence farming, and the population around Keetmanshoop is no exception. Other economical opportunities are limited in the area. Poverty is widespread and the communal lands are home to the majority of the Nama people. The 1.675 000 hectares of communal land provide the livelihood for approx. 3000 communal farmers today (Kuiper & Meadows, 2002). Mainly small stock is kept and goats are the dominating group. This has some significance for the resiliance of the ecosystem, since goats are known to be more aggressive "browsers" than the "grazing" sheep: they rather rip plant parts out instead of neatly biting them off, thus putting more stress on the vegetation. Moreover, they browse on higher plant components so that a strategic self protection of certain growth forms is diminished (Wolkenhauer, 2003).

The Nabaos Observatory is located on the Nuwefontein communal land and is used primarily by the villagers of Nuwefontein itself, which is located approx. 1 km to the Northwest. Based on data from 2003, the village consists of 11 households 7 of which possessed 622 goats, 13 donkeys and 4 sheep. Two further settlements exert an influence on the observatory, though to a lesser extent. Those are the settlements Nabaos with two households and a livestock of 288 goats, 255 sheep, 19 cattle, 11 donkeys and 10 horses, and the six households comprising the Tyrvlei settlement, which is situated further away. These three settlements share a communal area of 9813.7 hectare (Wolkenhauer, 2003).

The Gellap Ost Observatory is part of a governmental research station of the same name, situated approx. 20 km NW of Keetmanshoop. The farm comprises an area of 13,734 hectares and is managed by rotational grazing and low stock densities through a system of fenced camps (Vohland *et al.*, 2005). Main task of the research station is the breeding of Karakul sheep, but other animals are kept as well. In 2003, the stock comprised of 1719 sheep of varying races, 201 goats, 32 cattle and 5 horses. The grazing is strictly controlled by monitoring the defoliation of indicator plants. Further, the stocking rate of 9 hectare per small stock units (SSU) is kept below the recommendated carrying capacity of the Ministry of Agriculture of 6 hectare/ SSU on commercial and 10 hectare/ SSU on communal land. The communal land of Nabaos, by contrast, was at the same time clearly overstocked by 140% (Wolkenhauer, 2003).

5.2.5 Soils

Petersen (2008) mapped the soil units occurring on both observatories in detail. According to his studies, dominant soils are Cambisols and Regosols which together accounted for 85% of the studied profiles (n =40). The weakly developed Regosols occur on washes while stronger developed Cambisols occur on ridges with loamy parent material. In situ developed Cambisols occur also at the basis and footslopes of the shale outcrops. Petersen (2008) suggests that they developed during times of higher moisture regimes, followed by a period of massive transports of soil materials during which the loamy parent materials were deposited in the plains. Subsequently, a dryer era followed that continues to present times. Here, physical weathering and subsequent mass transport are the dominant processes. Thus, soil materials are translocated to the plains again where they cover the loamy phases. Apart from these deep soils, shallow Leptosols and epileptic Regosols were mapped on outcrops. As a third group, Fluvisols were classified which were distributed along the rivier structure in the South of the observatories.

The whole area is characterised by little variability of chemical soil properties. This and the predominance of Regosols with 50 to 55% is regarded by Petersen (2008) as an indicator for low significance of soil forming processes in the area. From the findings, he deduces three driving factors for soil properties in that area that also affect classification (according to WRB):

- type and age of substrate
- depths of the profiles
- content of coarse fragments

Generally, soils are characterised by relatively low EC-values due to regular deep drainage of the coarse materials. Further, remarkably high values of C (up to 0.8 %) and N (up to 0.15%) in the parent material were described which lead to very narrow C/N ratios ranging between 1 and 4. However, Petersen (2008) evaluates the N-contents of the parent material as relatively stable. Another common feature is the occurrence of the so-called ”desert pavement”; this term describes in this case the accumulation of fine to coarse gravel on the soil surface, a result of wind erosion of the silty substrates. In loamier soils, additionally a vesicular layer is found in the first millimetres to centimetres of the topsoil. These are assumed to reduce infiltration capacity (Volk & Geyger, 1970).

The distribution of soil types and their chemical and physical properties is very similar on both observatories (Petersen, 2008). Slight differences occur in terms of pH, which is tendencially increased in Nabaos, probably due to a higher proportion of thin calcareous layers in the parent material. Also, the inclination of the plains is slightly higher on Nabaos. The two observatories are regarded as comparable in terms of geology, petrography and morphology so that differences in topsoil properties on the two sides may be considered to be linked to different landuse systems.

5.3 Description of Sampled Units in a Hierarchical System

As on Soebatsfontein, the landscape was structured in a hierarchical system with nested units for the analysis of scale dependant variability of topsoils. The upmost hierarchical level was the D1-scale comprising two units belonging to the same landscape but being differentiated by the landuse factor: the term Nabaos is used here for the unit with communal farming, while the term Gellap describes the D1-unit with commercial land management.

On each D1-unit, subunits were described on the so-called D2-scale. Those are the "sedimentation areas" and the "outcrop areas". Further D2-units were identified, such as "main rivier" in the southern part of the Gellap observatory, "plateau" and "steep slopes" of high outcrops occurring on the sites; however, study sites were only established on "sedimentation area" and "outcrop area" since they occur within this work on both, Gellap and Nabaos, and are dominating the landscape.

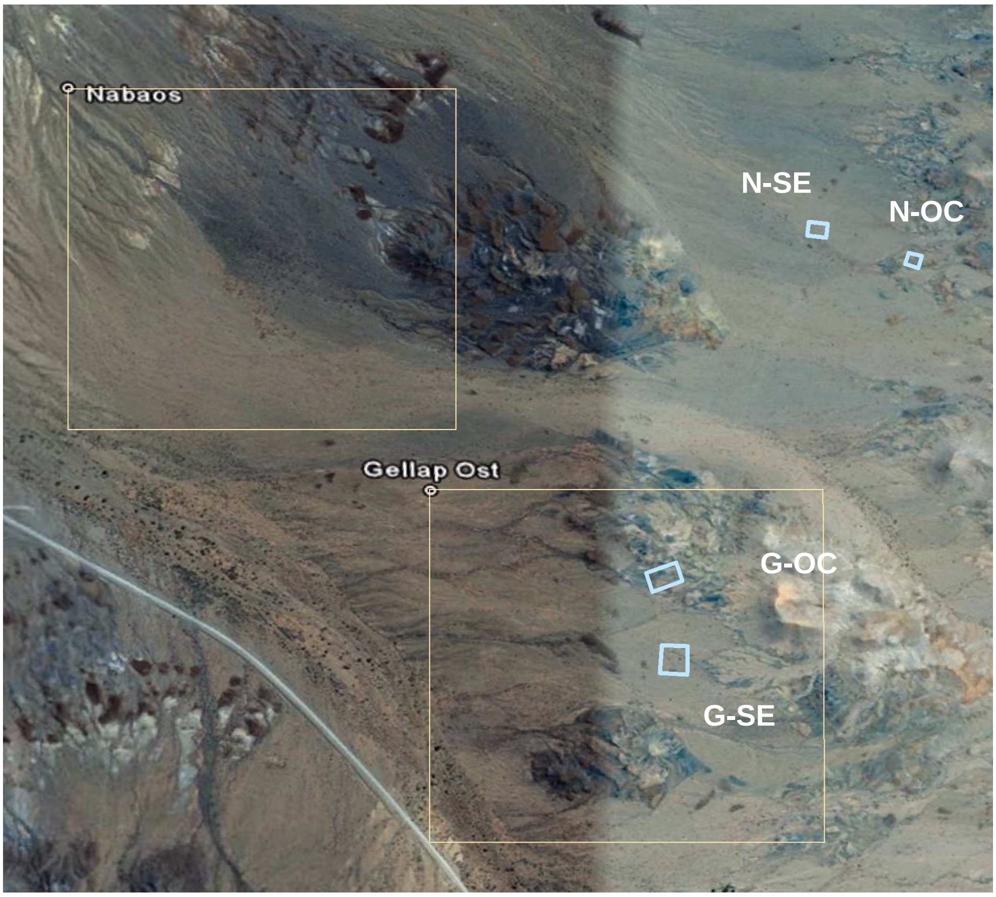


Fig. 5.4: Overview of the Gellap and Nabaos Observatories and the position of the four small scale study sites. N-SE: Nabaos, Sedimentation Area; N-OC: Nabaos, Outcrop Area; G-SE: Gellap Sedimentation Area; G-OC: Gellap Outcrop Area.

The sedimentation areas are located in the plains and consist of more or less stable sediments of the topographically higher shist and shale outcrops. Geomorphologically, the sedimentation areas are only weakly structured and subunits rather occur in terms of different aged sediment depositions. During strong rain events, sheet erosion may occur in the plains that proceeds depending on the erosive strength of the rain events along slightly depressed structures. These "Rivier"-units usually end up somewhere on their way to the main rivier in the South of the Observatories and only during scarce exceptionally strong events they break through to reach it. Further, these younger depositions incise older, more stable ones. Therefore, subunits on D3-scale were identified as so-called "Older Accumulation", "Younger Accumulation" and "Rivier". An example of the distribution of differently aged depositions is given in Fig. 5.5.

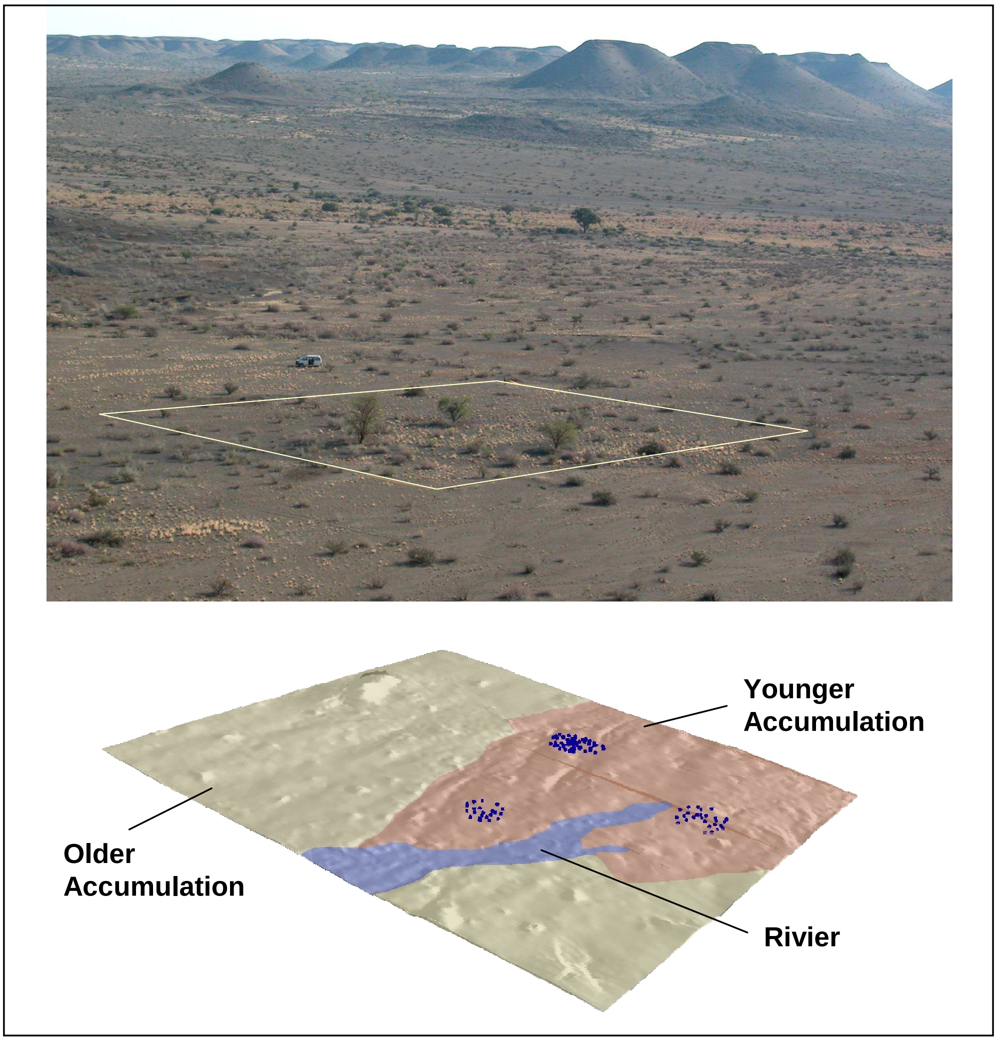


Fig. 5.5: Overview of the study site Gellap Sedimentation Area and the distribution of D3-units within. The blue dots indicate the crown area of the three *Albizia*-trees occurring on the site.

The outcrop areas are located topographically above the sedimentation areas. They consist of several soft ridges and rivier-like incisions inbetween that are filled with unconsolidated, rather coarse weathering products of the outcrops. Three kinds of ridges were identified on the outcrop areas and termed as follows:

- ”Red Ridge”: The red ridges consist of shale outcrops that appear reddish in colour. This kind of shale is platy, massivly structured and also reddish fine earth is only found in the upper few centimetres, filling up cracks. Plants are largely absent on this ridge since the coarse fragments are not suitable for growth in terms of water storage and rooting space.
- ”Black Ridge”: The black ridge also represents a shale outcrop though differences to the red ridge are striking: this kind of shist is physically weathering readily into fine, black gravels that can be easily crushed to even smaller particles. Fine earth fills up the multiple larger and smaller cracks that reach much deeper than on the red ridge. Plant growth is more strongly promoted on this outcrop compared to the red ridge; though the content of fine earth may be low, the fine breaking-up of the rock by mainly physical weathering is obviously sufficient to provide rooting space, and it is assumed that water might be stored in available form in deeper cracks. This is at least indicated by the occurrence of some shrubs such as *Catophractes alexandrii*.
- ”Brown Ridge”: Brown ridges have been found to have different genesis. Most of the brown ridges, namely the two on Gellap and the northern one of Nabaos, are more strongly weathered ridges of black shale. By contrast to the black ridges, they are less exposed and therefore more stable in terms of the erosion of fine earth. Soils are often rather shallow but may be deeper weathering and were classified according to WRB (2006) as Leptosols (see Appendix profile B.24) and Regosols (Appendix profile B.31). However, the stronger degree of weathering leads to the brownish colour and better conditions for vegetation. An exception is the southern brown ridge on the Nabaos outcrop area. Here, the sampling of a deep profile showed that this ridge consists of an older accumulation of sediments that must have been stable for a long period and probably further weathered in situ.

One additional D3-unit was sampled that occurs on both, sedimentation areas and outcrops areas. At times, the incisions of accumulation areas also referred to as ”Riviers” and ridge features integrate some slightly elevated areas that are vegetated in the otherwise vegetation-free Rivier structure. These structures are referred to as ”Rivier Islands”.

The last hierarchical level, units on the so-called D4- or micropatch-scale, considering structures in the size of several cm^2, were far less pronounced than in Soebatsfontein. BSC do not occur in this ecosystem (Büdel *et al.*, accepted). Rarely, physical crustings occurred instead, but were only present within the established study sites on

Fig. 5.6: Red shist outcrop (left) and black ridge (right)

one D3-unit in the Sedimentation Area in Gellap. Further soft crusts were observed in the sedimentation areas, but those were covered up to 5 cm by coarse particles, continually building up a transition to deeper layers. Also, these crusts were rather soft, more an accumulation of silty particles than a crust, and often multi-layered, intersected with further coarse sand layers. Therefore, topsoils with these crust-coarse sand layer- structures were regarded as the matrix or open soil to which other D4 units were compared.

Otherwise, the only microscale structuring was due to the existence of plants. Those were mostly shrubs reaching up to 2 m of height, few of them reaching a small tree-like habitus. Topsoil below the canopy of such trees was sampled twice: on each observatory once within the sedimentation area site. Generally it was expected that trees influence soil in approximately the same way as shrubs.

Grasses occurred only on Gellap and in denser patches only within the sedimentation areas. Although in this work usually only dwarf shrubs were taken into account for the analysis of mutual dependencies between species and soil, in one occasion miniprofiles were taken in topsoils of grass tussocks. This was especially interesting since infiltration rates and gravimetric water contents were also observed for this D4-unit on the same study site.

A list of all nested units on Gellap and Nabaos with abbreviations is given in Tab. 5.1.

D1	D2	D3	Abb	D4	Abb	Abbreviation
Nama Karoo on Shale, commercial farm land (G)	Sedimentation Area (SE)	Old Accumulation Zone	AO	Open Soil	O	**G-SE-AO-O**
				Grasses	G	**G-SE-AO-G**
				Crust	C	**G-SE-AO-C**
		Young Accumulation Zone	AY	Open Soil	O	**G-SE-AY-O**
				Shrub	P	**G-SE-AY-P**
				Tree	T	**G-SE-AY-T**
		Rivier	RV	Open Soil	O	**G-SE-RV-O**
	Outcrop Area (OC)	Brownish Ridge SE	BS	Open Soil	O	**G-OC-BS-O**
		Brownish Ridge NW	BN	Open Soil	O	**G-OC-BN-O**
		Reddish Ridge	RR	Open Soil	O	**G-OC-RR-O**
		Black Ridge	BR	Open Soil	O	**G-OC-BR-O**
		Rivier Island	RI	Open Soil	O	**G-OC-RI-O**
				Shrub	P	**G-OC-RI-P**
Nama Karoo on shale, communal land (N)	Sedimentation Area (SE)	Old AccumulationZone	AO	Open Soil	O	**N-SE-AO-O**
				Shrub	P	**N-SE-AO-P**
				Tree	T	**N-SE-AO-T**
		Young Accumulation Zone	AY	Open Soil	O	**N-SE-AY-O**
		Rivier Island	RI	Open Soil	O	**N-SE-RI-O**
				Shrub	P	**N-SE-RI-P**
		Rivier	RV	Open Soil	O	**N-SE-RV-O**
	Outcrop Area (OC)	Brownish Ridge S	BS	Open Soil	O	**N-OC-BS-O**
				Shrub	P	**N-OC-BS-P**
		Brownish Ridge N	BN	Open Soil	O	**N-OC-BN-O**
		Red Ridge	RR	Open Soil	O	**N-OC-RR-O**
		Black Ridge	BR	Open Soil	O	**N-OC-BR-O**
		Rivier Island	RI	Open Soil	O	**N-OC-RI-O**
				Shrub	P	**N-OC-RI-P**
		Rivier	RV	Open Soil	O	**N-OC-RV-O**

Tab. 5.1: Observatories Gellap and Nabaos: scheme of nested units.

5.4 Results and Discussion

5.4.1 Soilchemical Properties on the Gellap and Nabaos Observatories: an Inventory

5.4.1.1 Comparison of Chemical Soil Parameters with the BIOTA Transect Data Set

Like for the Soebatsfontein Observatory, the miniprofile data sets for the observatories Gellap and Nabaos were each analysed in terms of relevant statistical measures to allow a first assessment of the topsoil characteristics in these landscapes. This was achieved by a comparison with the same statistical measures of the BIOTA soil data base that includes all soil samples that were taken on the entire BIOTA transect which covers nearly 2,000 kilometers of length.

The topsoil characteristics of Gellap and Nabaos topsoils are largely similar. Both observatories have a medium mean pH in common that compares well to the mean of the transect data set, although pH is generally slightly increased in Nabaos topsoils. EC-values and watersoluble salts are comparatively low in both observatories compared to the transect data. However, salt accumulations may occur locally although values do not reach exceedingly high amounts. The salt level is slighlty increased on Gellap. Extraordinary are the high values for C_{org} and N_t and the resulting narrow C/N-ratios on both study sites; Petersen (2008) referred this to high geogenic backgrounds and regards the nitrogen contents in the parent material as relatively stable. Plantavailable phosphorus tends to be slightly increased on Nabaos and matches mean values of the transect.

Miniprofile Data Gellap									Transect Data								
Parameter	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**	**Parameter**	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**
pH$_{H2O}$	184	5.9	6.7	6.9	6.9	7.1	8.1	0.4	**pH$_{H2O}$**	3,473	3.8	6.2	6.8	6.9	7.8	10.4	1.2
pH$_{CaCl2}$	184	5.9	6.2	6.4	6.4	6.5	7.2	0.2	**pH$_{CaCl2}$**	3,474	3.3	5.3	6.4	6.3	7.2	9.9	1.2
EC$_{2.5}$ (µS/cm)	184	9	20	37	90	76	1,107	169	**EC$_{2.5}$ (µS/cm)**	3,473	1	15	42	364	110	35,300	1,376
EC$_5$ (µS/cm)	184	6	18	31	67	55	784	122	**EC$_5$ (µS/cm)**	3,472	2	12	32	229	81	20,300	809
C$_{inorg}$ (%)	16	0.00	0.00	0.00	0.01	0.01	0.10	0.03	**C$_{inorg}$ (%)**	2,194	0.00	0.00	0.01	0.20	0.10	6.39	0.55
C$_{org}$ (%)	184	0.11	0.19	0.27	0.32	0.42	0.99	0.18	**C$_{org}$ (%)**	3,013	0.03	0.17	0.28	0.41	0.46	9.95	0.55
N$_t$ (%)	184	0.07	0.11	0.12	0.12	0.14	0.20	0.02	**N$_t$ (%)**	3,356	0.00	0.03	0.04	0.06	0.09	1.66	0.06
C/N-ratio	184	1.2	1.8	2.2	2.5	3.2	4.9	0.9	**C/N-ratio**	3,007	0.6	6.0	8.2	8.2	9.8	75.3	4.4
S$_t$ (g/kg)	184	0.06	0.09	0.10	0.11	0.11	0.32	0.04	**S$_t$ (g/kg)**	2,994	0.00	0.03	0.08	0.28	0.12	75.24	2.19
Si$_t$ (%)	182	33.0	34.5	34.8	34.7	35.0	35.6	0.4	**Si$_t$ (%)**	2,871	3.0	33.9	36.3	36.6	39.4	46.3	5.0
Al$_t$ (%)	184	6.8	7.2	7.4	7.4	7.6	8.6	0.3	**Al$_t$ (%)**	3,011	0.1	4.0	5.5	5.0	6.5	12.2	2.2
Na$_t$ (g/kg)	184	5.0	5.8	6.1	6.1	6.4	8.1	0.5	**Na$_t$ (g/kg)**	3,010	0.1	2.9	6.0	7.1	9.5	31.3	5.5
K$_t$ (g/kg)	184	17.5	19.6	20.2	20.1	20.6	22.1	0.8	**K$_t$ (g/kg)**	2,957	0.0	17.2	22.6	21.6	28.1	67.0	10.6
K$_{dl}$ (g/kg)	25	0.08	0.11	0.17	0.20	0.24	0.67	0.13	**K$_{dl}$ (g/kg)**	567	0.00	0.00	0.11	0.12	0.18	0.95	0.13
Ca$_t$ (g/kg)	184	3.2	3.7	4.1	4.2	4.4	10.1	0.9	**Ca$_t$ (g/kg)**	3,112	0.0	1.6	4.0	10.1	8.2	148.9	17.0
Mg$_t$ (g/kg)	184	5.6	6.4	6.7	6.7	7.0	9.9	0.5	**Mg$_t$ (g/kg)**	3,092	0.0	1.2	4.4	6.1	8.1	62.2	6.4
P$_t$ (g/kg)	184	0.34	0.40	0.42	0.43	0.44	0.87	0.07	**P$_t$ (g/kg)**	3,114	0.00	0.30	0.37	0.40	0.46	5.49	0.24
P$_{dl}$ (g/kg)	25	0.006	0.010	0.016	0.033	0.040	0.169	0.038	**P$_{dl}$ (g/kg)**	472	0.000	0.000	0.013	0.038	0.050	1.030	0.074
Ti$_t$ (g/kg)	184	3.64	3.90	4.00	4.04	4.08	5.36	0.25	**Ti$_t$ (g/kg)**	3,011	0.23	1.77	2.66	3.10	4.11	20.41	1.93
Fe$_t$ (g/kg)	184	28.4	32.9	33.7	33.9	34.4	44.8	2.0	**Fe$_t$ (g/kg)**	2,930	0.1	11.4	20.2	24.0	33.6	102.4	17.1
Mn$_t$ (g/kg)	184	0.29	0.33	0.36	0.39	0.38	1.71	0.18	**Mn$_t$ (g/kg)**	2,997	0.00	0.13	0.31	0.39	0.47	10.92	0.42
Cr$_t$ (mg/kg)	184	43	49	50	51	52	59	3	**Cr$_t$ (mg/kg)**	3,011	0	23	44	49	58	595	47
Cu$_t$ (mg/kg)	184	31	35	36	36	36	41	2	**Cu$_t$ (mg/kg)**	3,011	0	7	15	20	29	384	19
Ni$_t$ (mg/kg)	184	22	25	26	26	27	30	1	**Ni$_t$ (mg/kg)**	3,011	0	9	18	20	26	250	19
Zn$_t$ (mg/kg)	184	55	77	79	80	82	131	8	**Zn$_t$ (mg/kg)**	3,011	1	22	41	48	74	189	31
Pb$_t$ (mg/kg)	184	10	17	18	18	19	65	5	**Pb$_t$ (mg/kg)**	3,011	0	15	21	20	27	117	10
Ba$_t$ (mg/kg)	184	516	620	632	629	645	694	25	**Ba$_t$ (mg/kg)**	2,996	0	382	521	497	622	9,036	317
Sr$_t$ (mg/kg)	184	92	101	106	107	110	147	10	**Sr$_t$ (mg/kg)**	1,545	1	72	98	105	118	2,162	99
Zr$_t$ (mg/kg)	184	198	210	218	229	240	401	34	**Zr$_t$ (mg/kg)**	1,545	0	162	205	218	239	1,219	124

Tab. 5.2: Comparison of statistic measures of dynamic and geologic driven parameters between the miniprofile data set of Gellap and the BIOTA-transect data soil data set. Data for watersoluble salts see Appendix Tab. B.4.

Miniprofile Data Nabaos									Transect Data								
Parameter	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**	**Parameter**	**N**	**Min.**	**Perc. 25**	**Median**	**Mean**	**Perc. 75**	**Max.**	**SD**
pH$_{H2O}$	209	5.2	6.8	7.2	7.2	7.6	8.8	0.7	**pH$_{H2O}$**	3,473	3.8	6.2	6.8	6.9	7.8	10.4	1.2
pH$_{CaCl2}$	209	5.0	6.4	6.6	6.6	6.9	7.7	0.4	**pH$_{CaCl2}$**	3,474	3.3	5.3	6.4	6.3	7.2	9.9	1.2
EC$_{2.5}$ (µS/cm)	209	5	12	17	50	45	935	101	**EC$_{2.5}$ (µS/cm)**	3,473	1	15	42	364	110	35,300	1,376
EC$_{5}$ (µS/cm)	209	5	9	14	42	40	750	81	**EC$_{5}$ (µS/cm)**	3,472	2	12	32	229	81	20,300	809
C$_{inorg}$ (%)	92	0.00	0.00	0.00	0.08	0.02	0.83	0.19	**C$_{inorg}$ (%)**	2,194	0.00	0.00	0.01	0.20	0.10	6.39	0.55
C$_{org}$ (%)	209	0.09	0.13	0.21	0.27	0.33	1.17	0.20	**C$_{org}$ (%)**	3,013	0.03	0.17	0.28	0.41	0.46	9.95	0.55
N$_{t}$ (%)	209	0.08	0.10	0.11	0.11	0.12	0.19	0.02	**N$_{t}$ (%)**	3,356	0.00	0.03	0.04	0.06	0.09	1.66	0.06
C/N-ratio	209	0.9	1.2	1.9	2.3	3.0	6.4	1.3	**C/N-ratio**	3,007	0.6	6.0	8.2	8.2	9.8	75.3	4.4
S$_{t}$ (g/kg)									**S$_{t}$ (g/kg)**	2,994	0.00	0.03	0.08	0.28	0.12	75.24	2.19
Si$_{t}$ (%)									**Si$_{t}$ (%)**	2,871	3.0	33.9	36.3	36.6	39.4	46.3	5.0
Al$_{t}$ (%)									**Al$_{t}$ (%)**	3,011	0.1	4.0	5.5	5.0	6.5	12.2	2.2
Na$_{t}$ (g/kg)									**Na$_{t}$ (g/kg)**	3,010	0.1	2.9	6.0	7.1	9.5	31.3	5.5
K$_{t}$ (g/kg)									**K$_{t}$ (g/kg)**	2,957	0.0	17.2	22.6	21.6	28.1	67.0	10.6
K$_{dl}$ (g/kg)	29	0.06	0.11	0.13	0.21	0.27	0.59	0.17	**K$_{dl}$ (g/kg)**	567	0.00	0.00	0.11	0.12	0.18	0.95	0.13
Ca$_{t}$ (g/kg)									**Ca$_{t}$ (g/kg)**	3,112	0.0	1.6	4.0	10.1	8.2	148.9	17.0
Mg$_{t}$ (g/kg)									**Mg$_{t}$ (g/kg)**	3,092	0.0	1.2	4.4	6.1	8.1	62.2	6.4
P$_{t}$ (g/kg)									**P$_{t}$ (g/kg)**	3,114	0.00	0.30	0.37	0.40	0.46	5.49	0.24
P$_{dl}$ (g/kg)	29	0.008	0.017	0.027	0.035	0.034	0.202	0.036	**P$_{dl}$ (g/kg)**	472	0.000	0.000	0.013	0.038	0.050	1.030	0.074
Ti$_{t}$ (g/kg)									**Ti$_{t}$ (g/kg)**	3,011	0.23	1.77	2.66	3.10	4.11	20.41	1.93
Fe$_{t}$ (g/kg)									**Fe$_{t}$ (g/kg)**	2,930	0.1	11.4	20.2	24.0	33.6	102.4	17.1
Mn$_{t}$ (g/kg)									**Mn$_{t}$ (g/kg)**	2,997	0.00	0.13	0.31	0.39	0.47	10.92	0.42
Cr$_{t}$ (mg/kg)									**Cr$_{t}$ (mg/kg)**	3,011	0	23	44	49	58	595	47
Cu$_{t}$ (mg/kg)									**Cu$_{t}$ (mg/kg)**	3,011	0	7	15	20	29	384	19
Ni$_{t}$ (mg/kg)									**Ni$_{t}$ (mg/kg)**	3,011	0	9	18	20	26	250	19
Zn$_{t}$ (mg/kg)									**Zn$_{t}$ (mg/kg)**	3,011	1	22	41	48	74	189	31
Pb$_{t}$ (mg/kg)									**Pb$_{t}$ (mg/kg)**	3,011	0	15	21	20	27	117	10
Ba$_{t}$ (mg/kg)									**Ba$_{t}$ (mg/kg)**	2,996	0	382	521	497	622	9,036	317
Sr$_{t}$ (mg/kg)									**Sr$_{t}$ (mg/kg)**	1,545	1	72	98	105	118	2,162	99
Zr$_{t}$ (mg/kg)									**Zr$_{t}$ (mg/kg)**	1,545	0	162	205	218	239	1,219	124

Tab. 5.3: Comparison of statistic measures of dynamic and geologic driven parameters between the miniprofile data set of Nabaos and the BIOTA-transect data soil data set. Data for watersoluble salts see Appendix Tab. B.5.

When comparing Gellap and Nabaos topsoils separately for the same geomorphological units (D2-sites "Sedimentation Area" and "Outcrop Area"), some of the observations become clearer:

	Sedimentation Area				**Outcrop Area**			
	Gellap		**Nabaos**		**Gellap**		**Nabaos**	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH$_{H2O}$	15	7.0 ± 0.2	17	7.2 ± 0.4	25	7.0 * ± 0.6	25	7.4 * ± 0.7
pH$_{CaCl2}$	15	6.4 ± 0.1	17	6.5 ± 0.3	25	6.4 * ± 0.2	25	6.8 * ± 0.5
EC$_{2.5}$ [µS/cm]	15	49 * ± 42	17	12 * ± 4	25	103 * ± 232	25	28 * ± 24
EC$_5$ [µS/cm]	15	32 * ± 27	17	9 * ± 3	25	82 * ± 173	25	25 * ± 23
C$_{org}$ [%]	15	0.26 * ± 0.06	17	0.15 * ± 0.02	25	0.24 ± 0.14	25	0.25 ± 0.12
N$_t$ [%]	15	0.12 * ± 0.01	17	0.11 * ± <0.01	25	0.10 ± 0.02	25	0.10 ± 0.01
C/N-ratio	15	2.1 * ± 0.4	17	1.4 * ± 0.2	25	2.2 ± 1.0	25	2.6 ± 1.2
K$_{dl}$ [g/kg]	6	0.18 ± 0.09	6	0.21 ± 0.19	9	0.14 ± 0.06	9	0.12 ± 0.05
P$_{dl}$ [g/kg]	6	0.014 * ± 0.003	6	0.021 * ± 0.007	9	0.054 ± 0.056	9	0.043 ± 0.060
Cl$_{we}$ [mg/l]	6	1.4 * ± 0.6	6	0.6 * ± <0.1	9	8.4 * ± 17.8	10	1.7 * ± 1.5
NO$_{3we}$ [mg/l]	6	69.8 * ± 89.2	6	0.3 * ± 0.3	9	38.7 * ± 46.5	10	8.5 * ± 16.9
SO$_{4we}$ [mg/l]	6	13.2 * ± 23.4	6	1.1 * ± 0.2	9	29.4 ± 60.1	10	7.1 ± 8.6
Ca$_{we}$ [mg/l]	6	22.7 * ± 17.9	6	4.6 * ± 1.9	9	22.6 ± 22.0	10	11.3 ± 9.3
Mg$_{we}$ [mg/l]	6	6.6 * ± 5.0	6	1.9 * ± 1.1	9	8.8 ± 8.9	9	5.3 ± 3.2
K$_{we}$ [mg/l]	6	7.9 ± 5.1	6	3.8 ± 3.5	9	11.2 ± 6.3	10	8.9 ± 6.4
Na$_{we}$ [mg/l]	6	3.6 * ± 3.1	6	1.6 * ± 0.9	9	10.4 ± 14.1	10	4.7 ± 2.8

Tab. 5.4: Comparison of weighted means over 0-10 cm topsoil for dynamic soil properties on Gellap and Nabaos with regard to the D2-sites. For the comparison only those D3 units were used that occur on both observatories. SD = Standard Deviation. * = significant differences with $p < 0.05$.

The previously observed slightly increased pH-values on the Nabaos side only apply significantly to the Outcrop Area while diffences in salts, e.g. expressed by EC-values, are significant on both D2-units and always show less salts in Nabaos. While C$_{org}$, N$_t$ and P$_{dl}$-values show no testable differences in the outcrop habitats, significant differences occur in the sedimentation areas: C$_{org}$ is strongly increased in Gellap, as is N$_t$, though to a lesser but significant extent. These differences are obviously ecologically effective, which is further underlined by the NO$_{3we}$-values that are on both, Sedimentation and Outcrop Area, manifold and significantly increased on Gellap. Also of ecological interest may be the increased SO$_{4we}$-content in Gellap topsoils.

5.4.2 Variability on D3-Scale

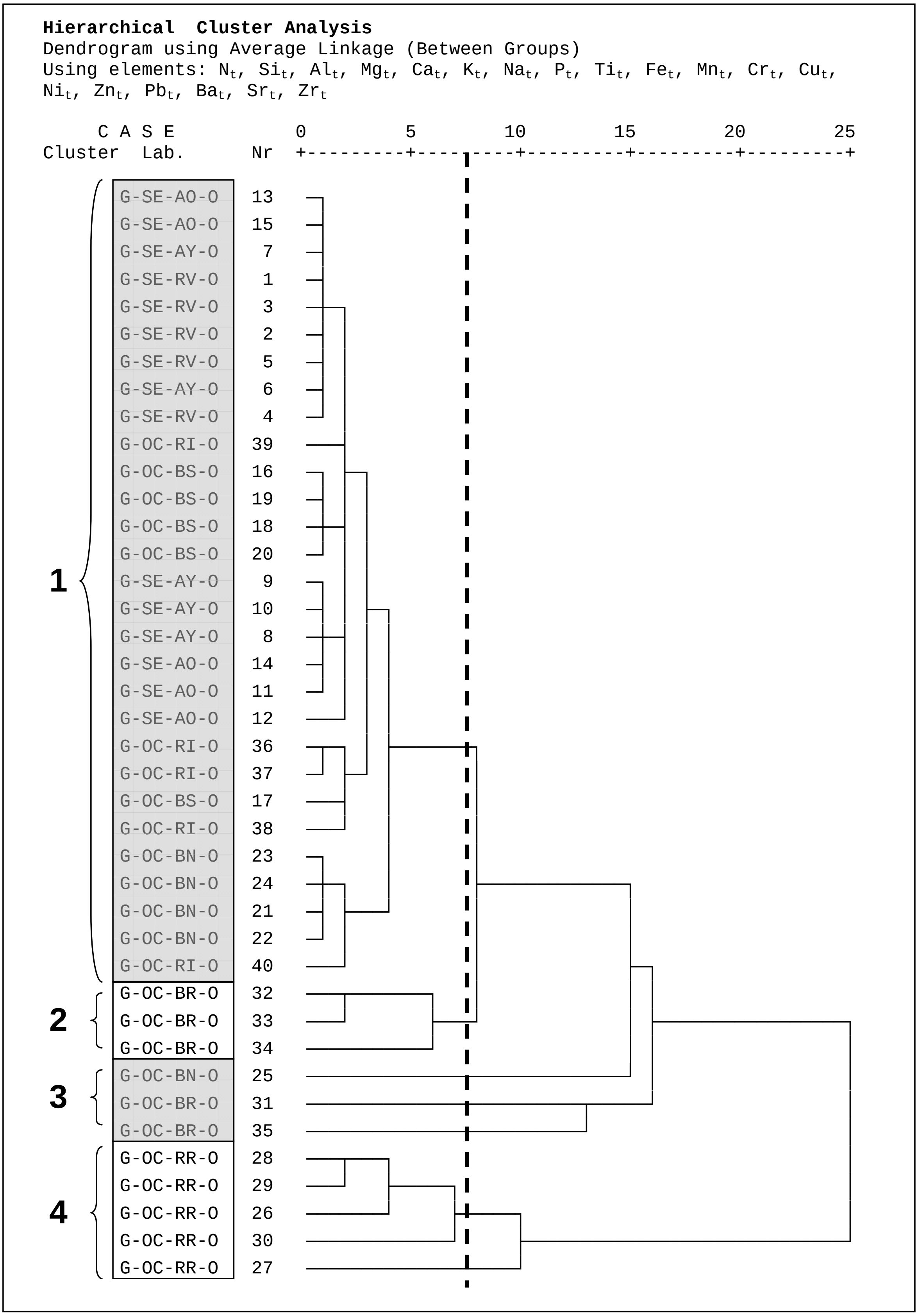
In the following chapter, it is analysed to which degree D3-units impact on soil variability. For a first overview, a hierarchical cluster analysis is conducted for the Gellap sites that involved total element contents. In a second approach, D3-units are regarded separately for the Sedimentation Areas and the Outcrop Areas. Since for all D3-units Open Soil samples were taken, only this data was referred to in the analysis for comparability reasons. Further, the variability of parent material was assessed by comparing the amounts of total element contents of the XRF analysis which were only available for samples of Gellap soils (compare 2.3).

5.4.2.1 Finding Main Patterns within D3-units: Cluster Analysis of Total Element Data

The results of the hierarchical cluster analysis that involved weighted means of each miniprofile for all total element contents are presented in Fig. 5.7.

The dendrogram was structured into four clusters of which cluster three consists of three individual miniprofiles that were originally treated as single "clusters" by the analysis. Cluster 1 comprises the bulk of samples which involve translocated sediments and more strongly in-situ weathered topsoils on ridges. Further, when regarding these results it is apparent that a structuring of the data is dominated by samples taken on ridges that were termed as "Black Outcrop" (G-OC-BR), making up Cluster 2 and 3, and "Red Outcrop" (G-OC-RR), being grouped to Cluster 4.

Usually, cluster analyses are conducted with the aim to classify data of which a grouping is not previously known. In this case, the hierarchical cluster analysis is used in a different sense: samples have been taken with regard to nested, hierarchical units that were determined with regard to morphological properties, vegetational characteristics and assumed geological differences. With the cluster analysis it is assessed to which degree homo- or heterogeneous preconditions exist in terms of geologic properties of topsoils before further analyses of D3-units were conducted with regard to more dynamic parameters.



Hierarchical Cluster Analysis
Dendrogram using Average Linkage (Between Groups)
Using elements: N_t, Si_t, Al_t, Mg_t, Ca_t, K_t, Na_t, P_t, Ti_t, Fe_t, Mn_t, Cr_t, Cu_t, Ni_t, Zn_t, Pb_t, Ba_t, Sr_t, Zr_t

Fig. 5.7: Hierarchical cluster analysis of weighted means across 0-10 cm of each miniprofile with regard to total element contents of the Gellap data set.

5.4.2.2 D3-units Generating Variability

D3-Variability on Sedimentation Areas in Gellap and Nabaos When regarding the variability of D3-units on the Sedimentation Areas of Gellap and Nabaos, only little evidence of groupings in accordance to the D3-units is given (see Appendix Fig. B.3 to Fig. B.35). An exception is the D3-unit "Rivier" on Gellap (G-SE-RV), which shows significant differences to other D3-units on Gellap with regard to pH, EC, C_{org} and C/N-ratio. However, these differences are still very small: the significant difference of pH_{H2O}, for instance, only consists of 0.1 pH-units compared to the Old Accumulation (G-SE-AO), which might hardly have a strong impact on the ecosystem; the difference to the Younger Accumulation (G-SE-AY) is higher with 0.4 pH-units and thus more likely to exhibit an effect on the system. EC-values are generally low in Gellap and Nabaos, but lowest within the three Gellap units on the Rivier-unit (G-SE-RV). While the amounts of N_t are stable, C_{org} ranges on Gellap between 0.22 and 0.30 %, whereupon the difference between G-SE-AY and G-SE-RV is significant. The same is valid for C/N-ratio.

On the Nabaos site, the grouping of parameters in accordance to their D3-affiliation is even less pronounced. The only site that shows a difference is the "Rivier Island" (N-SE-RI) in terms of pH_{CaCl2} and EC_5.

The comparison between Gellap and Nabaos D3-units confirms the results of findings stated in Tab. 5.4: pH-values are approximately on the same level, EC-values are lower on Nabaos, as are C_{org}, N_t and C/N-ratios.

D3-Variability on Outcrop-Areas in Gellap and Nabaos The Outcrop Areas of Gellap and Nabaos exhibited a stronger grouping compared to the Sedimentation Areas (see Appendix Fig. B.4 to Fig. B.38). However, although D3-units were largely the same, the impact of specific D3-units on variability varied on both sites; on Gellap, the "Red Ridge" (G-OC-RR), an outcrop consisting of a platy to massive kind of shale than the adjacent finer structured "Black Ridge" (G-OC-BR) outcrops, showed significantly increased pH-values. In terms of EC-values, the "Rivier Island"-site (G-OC-RI) showed a strikingly high variability and $Corg$, N_t and C/N-ratios were noticeably increased on the "Black Ridge" (G-OC-BR).

On Nabaos, especially the Northern Brown Ridge D3-unit (N-OC-BN) was distinct from the other units. This applied to increased values of pH and EC. Further, samples taken on less weathered units (N-OC-BN, N-OC-RR, N-OC-BR) had significantly increased $C\text{-}_{org}$-contents and related C/N-ratios compared to the more weathered D3-units (Southern Brown Ridge (N-OC-BS), Rivier Island (N-OC-RI), Rivier (N-OC-RV)).

The difference between C_{org}-values on outcrops and weathered material also applies to Gellap with regard to the Black Ridge (G-OC-BR). The fact that the Northern Brown Ridges (OC-BN) and Red Ridges (OC-RR) of Gellap and Nabaos do not show similar tendencies indicates the geological variability of outcrops and ridges between

Gellap and Nabaos although they were regarded as morphologically similar.

D3-Variability of Total Element Contents on Gellap Sedimentation and Outcrop Area Between the D3-units on the Sedimentation site, significant differences exist between all three of them in terms of P_t and Mn_t. In addition, the Rivier-unit (G-SE-RV) differs from the other two units significantly with regard to S_t and Na_t.

The difference between typical outcrop and more strongly weathered D3-units on the Outcrop Area becomes even clearer when regarding the total element contents. The data clearly shows that samples taken from the "Red Ridge" (G-OC-RR) are distinct from others by significantly higher P_t, Fe_t and Mn_t-values. The "Black Ridge" (G-OC-BR), is characterised by increased Al_t-values and both units show strikingly decreased Si_t and increased Ti_t-values.

Generally it can be stated that total element contents of the Sedimentation Area site resemble in most cases those of the more strongly weathered D3-units of the Outcrop site. Only those ridges with low weathering degree are strongly differing in properties from other D3-units.

5.4.3 Discussion of D3-Variability

While in Soebatsfontein the structuring of the landscapes into D3-units showed the strongest contribution on overall variability with regard to many soil properties compared to groups on other scales, the structuring on D3-scale is far less determinative in Gellap and Nabaos. This could be shown by both, cluster analysis and particular comparison of D3-units within the four D2-sites. The only strong differentiation could be identified for samples taken on outcrop ridges that were only slightly weathered. Here, samples of the so-called "Red Ridge", a more bulky shale, are distinguished from samples of the "Black Ridge", which is also a shale outcrop that in contrast to the Red Ridge weathers into much finer fragments.

In some soil properties, the outcrop topsoils resemble one another, in others, they differ in terms of high contents of particular total element contents, of which Ca_t is probably the factor implicating the highest importance for the ecosystem considering e.g. its role in pH-determination. In Nabaos, for instance, where outcrops were found that contained thin calcareous bands (Petersen, 2008), pH-values are generally slightly increased compared to Gellap. However, the variability increasing effects of the outcrops are a local phenomenon; gradients are dissolved by translocation and mixture of the weathering materials so that all other D3-units on both D2-sites show rather homogenous soil properties and differences are only found for dynamic parameters. Petersen (2008) described the underlying large scale processes that cause the homogenisation: landscape dynamics are characterised by continuing generation of weathering material in the outcrop areas and a subsequent translocation of the sediments into the plains where they are further transported along the inclination gradient in direction to the main rivier under further particle size reduction. Own observations after an exceptionally strong rain event of 68 mm on April 5th, 2005 confirm this assumption (see Fig. 5.8). While the study sites were not accessible during the thunderstorm, signs of considerable mass transport were clearly visible a day later.

Fig. 5.8: Signs of sheet erosion after a 68 mm rain event in April 2005 on Nabaos.

Observed differences between D3-units are therefore rather determined by the stability of the sediments that in turn controls in-situ weathering. This becomes clear when comparing more dynamic parameters of young sediments such as the "Rivier"-unit with older, more stable sediments, e.g. of the "Old Accumulation": pH-values are higher and C_{org}-values lower on "Rivier"-topsoils, since biological activity is higher on the more stable sites. On the other hand, EC-values are lower since coarser texture and higher infiltration rates of the Rivier soils and more frequent flooding lead to salt leaching processes.

5.4.4 Variability on D4-Scale: Mutual Dependencies between Shrubs and Soil Properties

Comparative data between D4 units Plant Canopies (= P) and Open Soil (O) of the same D3-unit are available for the two sites in Gellap-Ost and four sites in Nabaos. The D3-units under shrubs were sampled with regard to the following species:

- G-SE-AY-P: *Catophractes alexandrii*
- G-OC-RI-P: *Catophractes alexandrii*
- G-SE-AY-T: *Albicia anthelminthica* (all samples taken below the same tree)
- N-SE-AO-P: *Cardaba aphylla, Phaeoptilon sponosa* (3 miniprofiles), clump of *Boscia foetia* and *Phaeoptilon spinosa*
- N-SE-AO-T: *Acacia mellifera* (all samples taken below the same tree)
- N-SE-RI-P: *Phaeoptilon spinosa* (3 miniprofiles), *Rhigozum trichotomum* (2 miniprofiles)
- N-OC-BS-P: *Boscia foetida* (2 miniprofiles), *Phaeoptilon spinosa*, clump of *Boscia foetida* and *Cardaba aphylla* (two miniprofiles of the same clump)

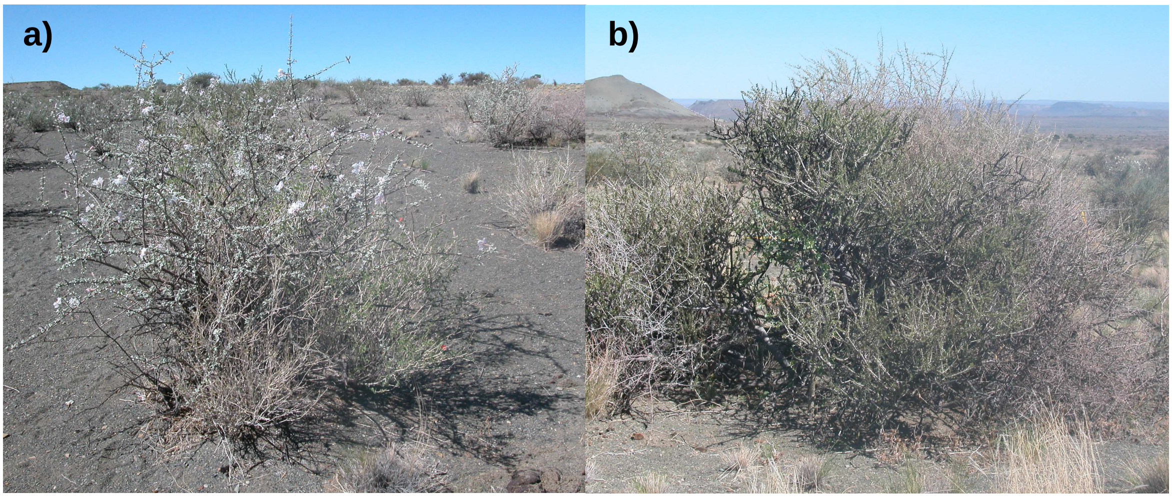


Fig. 5.9: Shrubs occuring in the Nama Karoo: a) *Catophractes alexandrii* (here: on Gellap), b) *Boscia foetida* (here: on Nabaos).

5.4.4.1 Significance Tests within the complete Data Set

In Soebatsfontein, a standardisation procedure was applied as a method to increase the sample number for statistical tests and therefore make it possible to detect finer differences between D4-groups (see Chapter 2.4.5). The same is adopted for analyses of shrub influence on soil properties in Gellap and Nabaos. Significant differences in the mean value of selected soil properties between Plant Canopy and Open Soil samples of different layers are given in Tab. 5.5 and Tab. 5.6.

	0-1		1-5		5-10	
Parameter	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
C_{org} [%]	20	0.16 ± 0.13 *	20	0.18 ± 0.12 *	20	0.14 ± 0.07 *
N_t [%]	20	0.019 ± 0.016 *	20	0.013 ± 0.013	20	0.003 ± 0.010
C/N-ratio	20	0.8 ± 0.6 *	20	1.2 ± 0.6 *	20	1.1 ± 0.4 *
P_{dl} [g/kg]	8	-0.01 ± 0.005 *	0	-	0	-

Tab. 5.5: Gellap: Comparison of Open Soil (O) and Plant Canopy (P) soil for the three individual layers. Presented is the difference of mean of Plant Canopy samples compared to Open Soil after standardisation of the data set (explanation see Chapter 2.4.5). Negative values indicate lower contents on Plant Canopy sites compared to Open Soil.

In Gellap, far less significant differences were obtained than in Nabaos, but it has to be considered that only two Shrub/ Open Soil groups were available for this site while on Nabaos four of such groups were involved in the analysis. However, the detected trends are widely the same for the two observatories, although differences are generally less distinct on Gellap. Compared to Open Soil, C_{org} is significantly increased in Shrub Canopy samples in all layers on both observatories. Interestingly, on Nabaos, the mean increase below shrubs is much stronger than in Gellap. Also, while the accumulation of C_{org} is approx. constant with 0.16 - 0.14 % in all layers on Gellap, a clear gradient with depth is apparent in Nabaos with relative increased values from 0.5% in the first layer to 0.16% in layer 5-10 cm. The same trend is valid for N_t, although on Gellap only differences of the first layer are significant. Again, on Nabaos differences are clearly stronger (more than double in all layers) and gradually decrease with depth. C/N-ratio is significantly wider in all layers on both observatories. As for C_{org} and N_t, in Nabaos C/N-ratios become narrower with depth and reach Gellap level in the deepest topsoil layer; in contrast to Gellap, C/N ratio differences between Shrub Canopy soils and Open Soil samples are more than three times stronger on Nabaos in the first centimetre, and still increased by factor 1.3 in the second.

Further significant differences for Gellap occur for P_{dl} (only analysed for the first layer) with lower values below plant canopies. This finding is not valid for Nabaos.

On the other hand, in Nabaos significant differences were found for most parameters that represent salt accumulation: especially EC-values were significantly increased below shrubs in all layers. Correspondingly, significant increases below Shrub Canopies compared to Open Soil were found for $NO3_{we}$, Ca_{we}, Mg_{we} and K_{we} in the first layer.

	0-1		1-5		5-10	
Parameter	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
$EC_{2.5}$ [µS/cm]	39	131 ± 127 *	39	109 ± 226 *	39	73 ± 131 *
EC_5 [µS/cm]	39	99 ± 81 *	39	96 ± 190 *	39	60 ± 105 *
C_{org} [%]	39	0.52 ± 0.27 *	39	0.26 ± 0.16 *	39	0.16 ± 0.14 *
N_t [%]	39	0.049 ± 0.021 *	39	0.029 ± 0.022 *	39	0.017 ± 0.013 *
C/N-ratio	39	2.6 ± 1.2 *	39	1.6 ± 0.9 *	39	1.1 ± 0.9 *
NO_{3we} [mg/l]	16	117 ± 234 *	16	198 ± 594	16	50 ± 147
Ca_{we} [mg/l]	16	32 ± 42 *	16	34 ± 89	16	33 ± 81
Mg_{we} [mg/l]	16	17 ± 19 *	16	18 ± 47	12	12 ± 26
K_{we} [mg/l]	16	31 ± 29 *	16	20 ± 31	16	7 ± 16

Tab. 5.6: Nabaos: Comparison of Open Soil (O) and Plant Canopy (P) soil for the three individual layers. Presented is the difference of mean of Plant Canopy samples compared to Open Soil after standardisation of the data set (explanation see Chapter 2.4.5). Negative values indicate lower contents on Plant Canopy sites compared to Open Soil.

Texture data was only available from composite samples of the five replica miniprofiles. To find differences between Open Soil (O) and Plant Canopy (P) units, texture data of Gellap and Nabaos was standardised and differences tested in the merged data set of the two observatories to increase the sampling number.

Tab. 5.7 summarises the results. Below plants, in all depths significantly lower contents of clay were determined in all depths. Otherwise, little accordance was found between the three layers: a trend was found of the first centimetre having less particles of sizes up to mS fraction in canopy soils but instead an increase of coarse sand. In deeper depth, particles up to mS-size are increased at plant sites, but coarse sand is decreased.

Fraction [%]	N	0-1 cm	1-5 cm	5-10 cm
Clay	12	-1.38 * ± 6.01	-2.23 * ± 4.56	-1.45 * ± 3.65
Silt	12	-0.67 ± 6.46	2.15 * ± 3.04	2.44 ± 4.32
fSi	12	0.03 ± 2.27	-0.25 ± 2.28	0.13 * ± 2.31
mSi	12	-0.06 * ± 2.71	0.46 ± 1.69	0.37 ± 1.40
cSi	12	-0.65 ± 3.55	1.94 * ± 1.75	1.94 * ± 1.80
Sand	12	2.06 ± 12.14	0.05 ± 7.33	-0.97 ± 7.55
fS	12	-0.94 ± 6.41	2.43 ± 3.59	2.17 ± 5.14
ffS	12	-0.70 ± 4.28	1.73 * ± 3.17	2.03 ± 3.87
cfS	12	-0.24 ± 2.16	0.69 ± 1.34	0.14 ± 1.42
mS	12	-0.64 ± 5.96	0.28 * ± 5.74	1.88 ± 4.77
cS	12	3.63 ± 16.32	-2.66 ± 5.90	-5.02 * ± 5.51
Pebbles	12	-3.95 ± 9.86	-0.71 ± 11.37	-5.67 * ± 9.21

Tab. 5.7: Comparison of particle size distribution of Open Soil (O) and Plant Canopy (P) soil within three individual layers: difference of mean of Plant Canopy samples compared to Open Soil after standardisation of the data set. Underlying data is all data pairs of Gellap and Nabaos. Means are presented with standard deviations. * indicates significance on 0.05 level. Negative values imply lower contents of a texture fraction on Canopy sites compared to Open Soil.

5.4.4.2 Significance Tests within Individual Sites

When regarding differences in soil characteristics below Shrub Canopies and Open Soil in Gellap and Nabaos, it appears that the parameters reacted very differently on the varying sites (Tab. 5.8 and Tab. 5.9): most consistent were the results for C_{org}, N_t and C/N- values. On five sites, C_{org} was significantly increased which consequently led to a significant widening of C/N-ratio although N_t also increased on all sites and significantly on Nabaos. The sixth site shows the same trends; however, these were not significant due to the low sample number.

pH-values showed no clear differences between canopy and open soils on Gellap, and showed strongly deviating results on Nabaos sites: in one of four cases pH decreased which was significant for pH_{H2O}; the other three cases showed the opposite trend, though this was not significant. EC-values also showed differences between Gellap and Nabaos. While in Nabaos shrubs increased EC-values, comparisons in Gellap revealed the opposite tendency, i.e. to decreased EC-values below plants. However, it has to be considered that on Gellap, comparisons were drawn regarding the Young Accumulation area while on Nabaos, this unit was not tested. Here, the Old Accumulation area was sampled instead. On the other hand, a comparison of the Young and

Old Accumulation area showed that there were no significant differences between these groups and that they were rather comparable. This is especially true for the texture analysis (see Appendix Tab. B.10).

	G-SE-AY				**G-OC-RI**			
	n	**O**	**n**	**P**	**n**	**O**	**n**	**P**
pH_{H2O}	5	6.8 ± 0.2	5	6.8 ± 0.2	5	6.6 ± 0.4	5	6.8 ± 0.1
pH_{CaCl2}	5	6.5 ± 0.2	5	6.3 ± 0.2	5	6.3 ± 0.1	5	6.3 ± 0.1
$EC_{2.5}$	5	66 ± 33	5	42 ± 34	5	358 ± 466	5	42 ± 12
EC_5	5	43 ± 23	5	37 ± 26	5	268 ± 348	5	31 ± 9
C_{org}	5	0.30 * ± 0.07	5	0.46 * ± 0.13	5	0.19 * ± 0.05	5	0.34 * ± 0.03
N_t	5	0.121 ± 0.006	5	0.134 ± 0.013	5	0.114 ± 0.022	5	0.118 ± 0.003
C/N-ratio	5	2.4 * ± 0.4	5	3.4 * ± 0.6	5	1.6 * ± 0.3	5	2.9 * ± 0.2

Tab. 5.8: Comparison Open Soil (O) and Shrub Canopy (P) units of the same D3-unit on Gellap with regard to dynamic soil properties. The data are based on weighted means over 0-10 cm topsoil calculated for each miniprofile.

	N-SE-AO				**N-SE-RI**			
	n	**O**	**n**	**P**	**n**	**O**	**n**	**P**
pH_{H2O}	6	7.2 ± 0.6	5	7.6 ± 0.5	5	7.0 ± 0.6	5	7.9 ± 0.6
pH_{CaCl2}	6	6.7 ± 0.4	5	6.7 ± 0.2	5	6.7 ± 0.1	5	7.0 ± 0.3
$EC_{2.5}$	6	14 * ± 6	5	49 * ± 20	5	20 ± 17	5	42 ± 22
EC_5	6	11 * ± 5	5	37 * ± 16	5	21 ± 21	5	47 ± 25
C_{org}	6	0.17 * ± 0.02	5	0.42 * ± 0.13	5	0.18 * ± 0.03	5	0.48 * ± 0.14
N_t	6	0.106 * ± 0.001	5	0.127 * ± 0.009	5	0.107 * ± 0.005	5	0.129 * ± 0.011
C/N-ratio	6	1.6 * ± 0.2	5	3.1 * ± 0.8	5	1.7 * ± 0.3	5	3.6 * ± 0.8

	N-OC-BS				**N-OC-RI**			
	n	**O**	**n**	**P**	**n**	**O**	**n**	**P**
pH_{H2O}	7	7.1 * ± 0.7	5	6.2 * ± 0.6	3	6.9 ± 0.1	3	7.6 ± 0.1
pH_{CaCl2}	7	6.6 ± 0.3	5	5.9 ± 0.6	3	6.3 ± 0.2	3	6.8 ± 0.1
$EC_{2.5}$	7	22 * ± 20	5	312 * ± 228	3	9 ± 1	3	29 ± 6
EC_5	7	18 * ± 14	5	257 * ± 186	3	8 ± 1	3	25 ± 5
C_{org}	7	0.11 * ± 0.01	5	0.39 * ± 0.15	3	0.14 ± 0.01	3	0.27 ± 0.03
N_t	7	0.101 * ± 0.003	5	0.142 * ± 0.019	3	0.102 ± 0.004	3	0.117 ± 0.004
C/N-ratio	7	1.1 * ± 0.1	5	2.7 * ± 0.8	3	1.4 ± 0.2	3	2.2 ± 0.3

Tab. 5.9: Comparison of Open Soil (O) and Shrub Canopy (P) units of the same D3-unit on Nabaos with regard to dynamic soil properties. The data are based on weighted means over 0-10 cm topsoil calculated for each miniprofile.

5.4.4.3 Threefactorial Analysis of Variance (ANOVA) including all sites of Gellap and Nabaos

The variability of soil properties was assessed by applying a three-factorial ANOVA on a data set comprising the two Gellap Shrub/ Open Soil groups and three Nabaos data pairs. One of the Shrub/ Open Soil data sets was omitted since only six miniprofiles (3 x Open Soil and 3 x Shrub Canopy) were taken on this particular site and the ANOVA application requires homogenous data sets comprising five miniprofiles in this case. It was decided that the omission of this site was acceptable: the unit was located on a single "Rivier Island", measuring only approx. 2 m^2 in size, thus all miniprofiles had to be taken under the same shrub on this relatively small area and the areal representativeness that is lost on that account in terms of the total study site is low.

Parameter	**Site**	**D4**	**Layer**	**Site * D4**	**Site * Layer**	**D4 * Layer**	**Site * D4 * Layer**	**Residual Variance**
C/N-ratio	13	**44**	**9**	5	**5.2**	1.3	2.8	19
C_{org}	9	**38**	**13**	5	**5.4**	**3.9**	3.5	22
N_t	7	**31**	**15**	9	**5.1**	**5.4**	1.6	27
K_{dl}	**32**	**17**	**-**	22	**-**	**-**	**-**	29
K_{we}	19	**17**	**4**	**33**	3.8	**2.5**	**6.3**	14
P_{dl}	**33**	8	**-**	16	**-**	**-**	**-**	43
SO_{4we}	**38**	6	1	**41**	4.5	0.8	**5.1**	3
Na_{we}	22	4	0	25	0.3	0.1	0.3	**48**
Mg_{we}	25	3	2	**40**	4.9	0.8	**5.2**	20
Ca_{we}	23	1	0	**39**	2.2	0.1	2.1	32
NO_{3we}	23	1	2	**32**	**7.2**	**1.4**	**6.9**	26
Cl_{we}	20	0.5	1	26	2.1	0.5	2.2	**48**
EC_5	11	0.4	0.3	22	2.1	0.6	2.1	**62**
pH_{CaCl2}	**37**	0.4	0.03	13	1.9	0.3	1.0	46
$EC_{2.5}$	11	0.2	0.2	21	1.8	0.7	1.6	**64**
pH_{H2O}	22	0.05	2	27	3.7	0.1	1.0	44

Tab. 5.10: Variance components (%) of the factors Site, D4-unit, Layer, combinations of these and non-explained residual variance. Boxes highlighted grey represent the highest variance components (the upper quantile) within a factor across all parameters.

By the application of ANOVA, the contribution of three defined factors and their interactions on total variability were tested. These factors were "Site" as a combination of Observatory, D2 and D3-unit, "D4", representing the data split into Open Soil (O) and Shrub Canopy (P) units, and "Layer", taking the sampling depths into account. The results are given in Tab. 5.10.

While in Soebatsfontein, the "Site" factor exhibited a strong influence up to 86% for pH_{H2O} on total variability within the data set for most parameters, this effect was far less pronounced in Gellap and Nabaos. Still, this factor reached values up to 38% for some soil properties, of which pH_{CaCl2}, SO_{4we}, K_{dl} and P_{dl} were highest.

The highest contribution to variance explanation by factor D4 and thus the differentiation of samples into Open Soil and Shrub Canopy samples is given by the parameters that are linked to organic matter: C/N-ratio with 44%, C_{org} with 38% and N_t with 31%. These are followed by the parameters K_{dl} and K_{we} that are also linked to decomposition of organic material. Variability of D4-units is lowest with regard to EC and pH-values; these are more strongly explained by the "Site" factor and the combination of the factors "Site" and "D4", indicating that a site-depending influence of D4-differentiation is given.

The sampling depth generally explains only few percentages of total variance, but at least explains between 13 and 15% total variability of the parameters C_{org} and N_t.

Non-explained residual variability, which is the variability within groups compared to variability between groups, is highest for pH-, EC- and P_{dl}-values. This is in so far interesting since at least pH showed a high degree of variance explanation after a comparable analysis on the Soebatsfontein Observatory.

In general, the previous findings are reflected again in the variance participation: where Shrub/ Open Soil differentiation resulted in different relationships on Gellap compared to Nabaos, the explanation of total variance is stronger for the factor combination Site*D4. This is valid for EC-values and some watersoluble salts. Where same differences between D4-units were obtained, factor D4 exhibits a strong percentage on total variability (C_{org}, N_t, C/N-ratio).

5.4.4.4 Twofactorial Analysis of Variance (ANOVA) for Individual Sites

For a more detailed overview on variance distribution within the data set, a two-way ANOVA was applied to all single sites comprising the factors "D4" and "Layer". The results are provided in Fig. 5.10.

The contribution of the factors and factor interactions on total variability strongly deviates between the sites. For pH_{H2O}, a large percentage of unexplained residual variance is visible for all sites; however, this fraction still varies between the sites from 43% to 86%. Also, D4-contribution varied from 1% to $\approx$ 50%. This goes along with the finding of the previous three-way ANOVA that revealed a strong contribution of the factor combination "Site*D4". Residual variances for C_{org}, N_t and C/N-ratio are much lower compared to the results of the parameter pH_{H2O}, as was shown in the three-way ANOVA. However, here again strong differences between the sites occur. On the Rivier Island in Gellaps' Outcrop Area (G-OC-RI) and the Brown Ridge of Nabaos' Outcrop Area (N-OC-BS) the low contribution of Layer and D4*Layer-interaction compared to the other sites are striking. This is also valid for pH_{H2O} and $EC_{2.5}$. On the other hand, the Sedimentation Area sites show stronger effects regarding these factors.

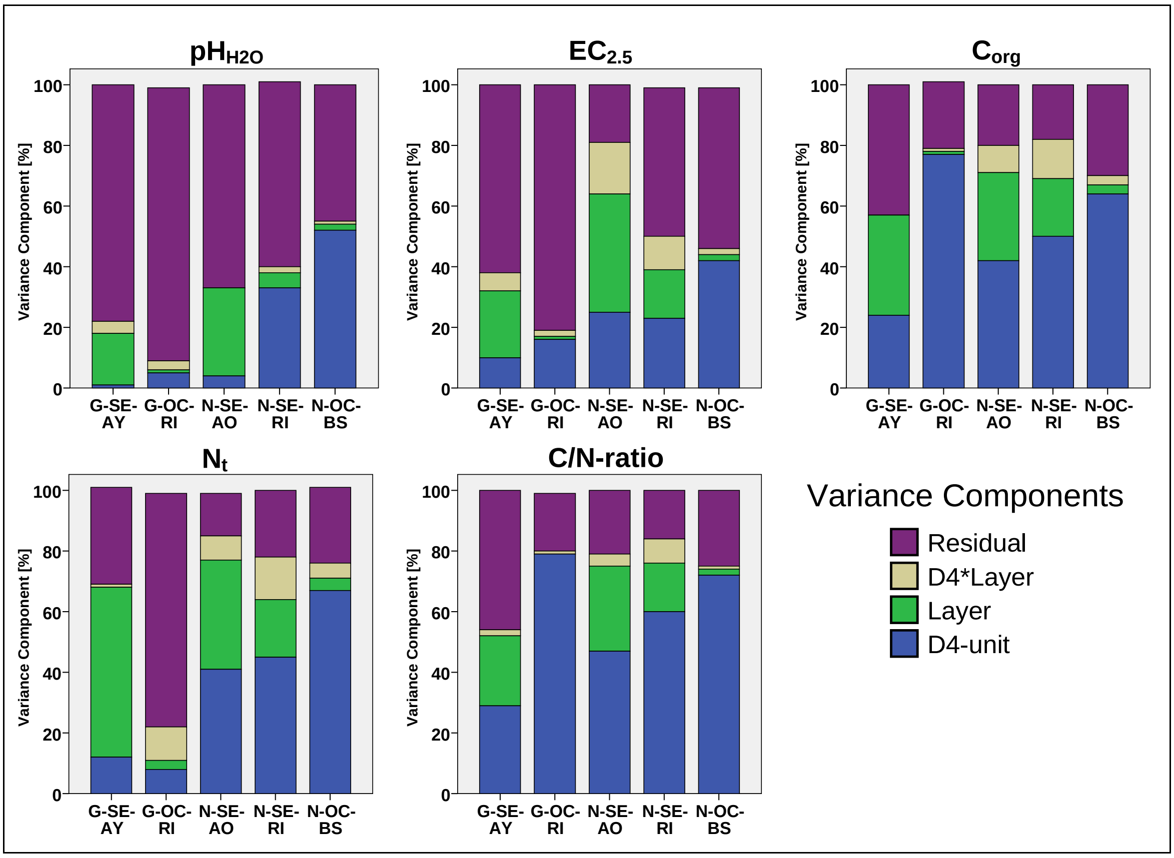


Fig. 5.10: Variance components of the factors D4-unit, Layer, combinations of these and non-explained residual variance determined by a two-way ANOVA in SPSS.

Also of interest are the variance fractions of the sites G-SE-AY (Gellap, Sedimentation Area, Younger Accumulation Area) and N-SE-AO (Nabaos, Sedimentation Area, Old Accumulation), which were assumed to be comparable sites of the two observatories, as texture analyses indicate (see 5.4.4.2). When regarding the single parameters, the fraction distribution of variance components of these two sites are oftenly similar, with higher total explanation percentage on the Nabaos site.

5.4.5 Discussion of Mutual Dependencies between Shrubs and Soil Properties

By comparing soil properties below Shrub Canopies with adjacent Open Soil patches, several effects could be shown: plants accumulated organic matter in the canopy zone, thus leading to significantly increased values of C_{org} and N_t and more humus-like C/N-ratios. On the other hand, these effects had different intensities with regard to the data sets of Nabaos and Gellap separately. Moreover, in Nabaos, a relative accumulation of salts could be detected below plants that was not detectable on study sites in Gellap. Here, a comparison of the single sites showed that plants rather exhibited the opposite effect of soils: salt indicating parameters such as EC-values were decreased below shrubs, though not significantly. On the other hand, P_{dl} showed significantly decreased values in canopy soils on Gellap, a finding that was not confirmed in the Nabaos data set. With regard to texture, an increase of fractions from medium silt to medium sand was found below plants from depth of one centimetre and deeper while in the first centimetre the opposite trend was true.

The texture differences indicate the trapping of airborne material by the plant crowns, a process that has often been stated for shrubs in dryland ecosystems. According to Herrmann (1996), particles < 20 μm are capable of long-term air suspension, a size which matches fractions up to the medium silt class. Fractions of 20 - 70 μm, which parallels coarse silt, are still suspended up to approx. 2 m in height. Very fine sand is transported by means of modified saltation, and fine sand to medium sand fractions are transported via saltation, a process which included vertical movements of up to 1.5 m above the surface. Coarse sand particles, however, are too heavy to be lifted upwards by wind. They are creeping above the surface and usually do not exceed a distance of more than a few metres. The fact that the first centimetre of topsoil shows the opposite trend may be explained by leaching processes, small scale water erosion on the exposed phytogenic mounds after canopy dripping or biological activity.

The accumulation of C_{org} and N_t in canopy areas is a commonly described process which is referred to the formation of so-called "fertility islands". Several factors such as the recycling of litter material in the crown area, the uptake of nutrients beyond the canopy zone, further enrichment by dust and particle trapping through wind and water erosion and the input of animal faeces contribute to this phenomenon. Depending on the state of litter composition, C/N-ratios tend to be wider under Canopies compared to Open Soil and may gradually decrease with depth. At this point, the special situation concerning C_{org} and N_t- contents in the regarded study sites has to be considered as well: Petersen (2008) first described the extraordinary high contents of these two parameter species within the parent material that led to strikingly low C/N-ratios within soil. Due to this phenomenon, an input of organic matter by plants leads to the unusual widening of C/N-ratios to more humus-like conditions. Petersen (2008) further states, that the N_t-fraction of the parent material is relatively stable whilst C_{org}-contents vary more strongly. He refers this to a relative depletion of C_{org}, but not of N_t, with increasing weathering which might involve the destructive force of radiation on bare soil. This leads to a decrease of C/N-ratio with weathering degree of the parent material, and thus lower C/N-ratios in topsoils compared to deeper soil layers. Therefore, three processes are apparently controlling the contents of C_{org} in soils:

1. biogenic processes, leading to a widening of C/N-ratios by C_{org}-input
2. weathering, leading most likely to a narrowing of C/N-ratios by loss of C_{org}
3. texture effects: erosion of fine particles within the first centimetres of soil leading to wider C/N-ratios by a pronounciation of parent material in form of sand which consists of shist

The dynamics of C and N behaviour and the actual contents of the shales are not completely discovered yet and shall not further be discussed at this point. Concerning the comparison of canopy and open soils, the results indicate a clear effect of biogenic C_{org} input since the absolute values of C and N below shrubs on Gellap and the more degraded Nabaos site are comparable.

Apart from C_{org} and N_t accumulations, the term "fertility islands" comprises enrichments in several other nutrients. Virginia & Jarrell (1983), for instance, reported enrichments of P, S, and K under mesquite (*Prosopis juliflora*). A detailed literature summary regarding this topic is provided in Chapter 3.3.1.

In terms of this nutrient enrichment, the two plant-available nutrient species K_{dl} and P_{dl} did not confirm the fertility island effect. While K_{dl} showed no significant effects at all, P_{dl} was even significantly decreased below plants on the Gellap sites. The same trend was previously observed for comparisons of Canopy and Open Soil samples in Soebatsfontein. Here it was assumed, that plants readily use this nutrient known as limiting so that it is not very surprising that in direct plant vicinity P_{dl}-levels are reduced. However, K_{dl} and P_{dl}-contents were only analysed for the first centimetre of topsoil. Therefore, a positive effect below this depth cannot be excluded.

On the other hand, increased amounts of watersoluble salt species and EC below crowns of Nabaos shrubs further indicated a fertility island formation. Among these watersoluble anions and cations are K_{we} and NO_{3we}. Why these effects were not found in Gellap remains an interesting question whose solution might also explain the fact, that C- and N-accumulation was far less pronounced below Gellap shrubs. It seems as if the island of fertility formation is generally less developed in Gellap. However, it has to be considered, that the analysis of Gellap Shrub/ Open Soil patches only comprised two D3-sites and thus 20 miniprofiles while on Nabaos sampling intensity was twice as high. Nevertheless, the observed effects are clear.

A hint regarding the reasons for this striking finding may lie within the soil property differences between Nabaos and Gellap in general. EC-values and watersoluble cations and anions were found to be on a relatively low level on both observatories. This statement is confirmed by previous findings of Petersen (2008) who analysed the observatories on the square kilometer scale and by describing deep soil profiles. Nevertheless, own results show that EC-values and contents of watersoluble cations and anions were clearly increased in Gellap soils; in terms of EC, values were found to be more than three times higher than in Nabaos.

The two BIOTA-observatories were established as twin-observatories that were comparable in their basic preconditions but were subject to different land-use systems for decades, as was pointed out in Chapter 5.2.4. Petersen (2008) confirmed the comparability of the two sites, albeit with restrictions: he found a slightly higher trend of pH-values in Nabaos and refers this to a higher proportion of thin calcareous layers in the parent material. Further, he points out that Nabaos is influenced by a larger catchment in the eastern surrounding, which causes a stronger drainage structure in the observatory. However, the Nabaos small scale study sites were not established within the actual observatory, but slightly northwards and with that outside of the younger drainage structure(see Fig. 5.4). The author therefore assumes largely comparable conditions between the Nabaos and Gellap observatories in terms of geologic parent materials.

It is accepted by several authors, that the Nabaos study site shows distinct signs of degradation, both in terms of soil and vegetation (Petersen, 2008; Wolkenhauer, 2003; Kuiper & Meadows, 2002). However, a clear effect in terms of chemical soil properties had not been substantiated so far. Adaptions of ecosystems to degradation has been reported by several authors (Allsopp, 1999; Schlesinger *et al.*, 1990). It is assumed that the development of resource patches (in the transition from grasslands to shrublands, see Schlesinger *et al.* (1990)) or the increase of such in scale (savannas, see e.g. Ludwig *et al.* (2000)) is a response of ecosystems to degradation that ensures a more efficient storage and use of water and nutrients when these become scarcer. It was also repeatedly suggested to use heterogeneity indices as a measure to monitor and evaluate degradation states in drylands (Tongway & Ludwig, 1997a; Schlesinger *et al.*, 1996).

The different findings from Shrub Canopy/ Open Soil comparisons in Gellap and Nabaos may be explained by the above-mentioned considerations. When the amount of water soluble cations and anions such as NO_{3we} and K_{we} are considered as favourable in terms of nutrient availability, because the underlying background values are very low and undesired salt effects can be excluded, then Nabaos soils may be regarded as depleted in comparison to Gellap soils. Moreover, the stronger development of resource or fertility islands in Nabaos, may be seen as a soil-based indicator of degradation *in sensu* Tongway & Ludwig (1997a). The occurrence of grasses in Gellap and the lack of it in Nabaos further supports this assumption, since a homogenous grass distribution decreases the scale of heterogeneity as could be shown by Schlesinger *et al.* (1996) by calculating semi-variograms for available N-species in grasslands and shrublands in the Chihuahuan Desert of New Mexico. In addition, the lack of grasses on Nabaos and the consequent stronger exposition of bare soil to radiation may increase the fertility island effect by an increased destruction of C_{org} in the vast open soil areas, as was discussed above.

Based on these models and theoretical frameworks, an implication for the current studies may be that on the overgrazed and depleted Nabaos-sites, plants facilitate their own growth area by a more efficient accumulation of nutrients than is the case for plants in Gellap. However, the kind of species underlying the analysis is also crucial: on Gellap, all shrubs that had been sampled belonged to the species *Cattophractes alexandrii*. One sample group was derived from the Younger Accumulation Area on the Sedimentation Area study site (G-SE-AY), the other was obtained from the Outcrop Area and here from the D3-unit "Rivier Island" (G-OC-RI). While the samples below shrub canopies on the Sedimentation Area were taken from five *C. alexandrii* individuals that were widely distributed across the D3-unit on a rectangle of approx. 15 x 40 m, the sampling of the Rivier-Island site was limited to approx. 14 x 14 m. However, here as well, at least 4 different shrubs were sampled.

Catophractes alexandrii is a thorny shrub that reaches approx. 2 m in height and is rather squarrose in habitus (see Fig. 5.9). The species was dominant on the chosen small scale study site and therefore chosen for the canopy sampling. On Nabaos, *C. alexandrii* occurred, too, but was by far less abundant. Here, shrubs occurred oftenly in relatively dense clumps of various species of which *Phaeoptilon spinosa*, *Rhigozum trichotomum*, *Cardaba aphylla* and *Boscia foetida* were dominant. Since the aim of the current study was to analyse differences between shrubs and open soil *per se*, the strategy was followed to sample shrubs that were representative for the particular study site. No focus was placed on species specific sampling, although the sample locations were described in detail in terms of species and a survey of the canopy area to eventually determine effects of phytomounds. Therefore, the sampled species on Gellap and Nabaos were different, and a species specific effect on the findings may not be excluded, especially because of the differences of canopy density. On the other hand, Wolkenhauer (2003) stated a different vegetation composition of the observatories as a consequence of the different grazing intensities that are seen as the major cause of degradation. Therefore, the fact that a shrub such as *C. alexandrii* is capable of growing in Gellap as a dominant species altough the rather squarrose habitat only allows a reduced generation of fertility islands below the canopy, while the dense bushy shrub clumps of other species typical for Nabaos, may justify the comparison of different species on the site. Nevertheless, it is regarded as most desirable to extend the conducted analysis to further shrub units involving the same species on both sites.

5.4.6 Further Interactions on the D4-Scale

Further D4-units were sampled, although far less frequently. Those are the only crust site on the Gellap Sedimentation Area (G-SE-AO-C), grassy micropatches on the same D3-unit (G-SE-AO-G) and two tree canopies: one located on Gellap (G-SE-AY-T) and the other on Nabaos Sedimentation Area (N-SE-AO-T). The latter D4-units were expected to behave similar to the Shrub Canopy soils (Tab. 5.11).

The Crust Soil was characterised by lower pH-values (in case of pH$_{H2O}$ significantly), and lower amounts of C$_{org}$ and N$_t$. Although not significant, a tendency of decreased salt contents on the crust site is clearly visible.

Regarding the soil taken in the rooting zone of grass tussocks, significant decreases of pH are detectable. C_{org} and N_t showed a tendency of increased values whereas C/N-ratio was wider. No significant differences occurred with regard to salt related parameters (EC-values, watersoluble cations and anions), although EC-values tended to be higher on Tussock sites compared to Open Soil.

Most interesting in this analysis was the question, whether the trees showed a similar effects on soil as the shrubs. Differences between Tree-samples and Open Soil were much more strongly pronounced on Gellap than on Nabaos. On the former observatory, EC, C_{org}, N_t and C/N-ratio were significantly increased. On the Nabaos site, these findings were confirmed as trends in terms of $EC_{2.5}$ and EC_5, and significantly for C_{org}, N_t and C/N-ratio.

	G-SE-AO						**G-SE-AY**				**N-SE-AO**			
	n	**O**	**n**	**C**	**n**	**G**	**n**	**O**	**n**	**T**	**n**	**O**	**n**	**T**
PH_{H2O}	5	7.1 ± 0.1	5	6.8 * ± 0.1	5	6.8 * ± 0.1	5	6.8 ± 0.2	5	7.1 ± 0.2	6	7.2 ± 0.6	3	7.4 ± 0.3
pH_{CaCl2}	5	6.4 ± 0.1	5	6.4 ± 0.1	5	6.2 ± 0.1	5	6.5 ± 0.2	5	6.6 ± <0.1	6	6.7 ± 0.4	3	6.2 ± 0.2
$EC_{2.5}$	5	59 ± 62	5	52 ± 14	5	64 ± 80	5	66 ± 33	5	264 * ± 211	6	14 ± 6	3	19 ± 3
EC_5	5	39 ± 38	5	38 ± 8	5	57 ± 51	5	43 ± 23	5	181 * ± 130	6	11 ± 5	3	14 ± 2
C_{org}	5	0.25 ± 0.05	5	0.21 ± 0.01	5	0.32 ± 0.08	5	0.30 ± 0.07	5	0.53 * ± 0.10	6	0.17 ± 0.02	3	0.24 * ± 0.03
N_t	5	0.119 ± 0.008	5	0.110 ± 0.001	5	0.125 ± 0.008	5	0.121 ± 0.006	5	0.154 * ± 0.009	6	0.106 ± 0.001	3	0.118 * ± 0.003
C/N-ratio	5	2.1 ± 0.2	5	1.9 ± 0.1	5	2.5 ± 0.5	5	2.4 ± 0.4	5	3.4 * ± 0.4	6	1.6 ± 0.2	3	2.0 * ± 0.2

Tab. 5.11: Comparison of the D4-units "Grass" (G), "Tree" (T) and "Crust" (C) with Open Soil (O) of the same D3-unit on sites in Gellap and Nabaos with regard to dynamic soil properties. The Data are based on weighted means of 0-10 cm topsoil calculated for each miniprofile. SD = Standard Deviation. * = significant differences with $p < 0.05$.

5.4.7 Discussion of further Interactions on the D4-Scale

In Chapter 5.4.5, the differences between shrubs of Gellap and Nabaos in terms of their capability to indicate changes in soil properties were discussed. As a result, Nabaos shrubs more strongly developed fertility islands than Gellap shrubs, which was attributed to the advanced degradation process in Nabaos. When comparing Open Soil patches with Canopy soil of trees on the two observatories, the contrary trend is true: in Gellap, under *Albicia anthelmintica* EC-values are manifold and in most cases significantly increased, while no significant differences were observed for *Acacia mellifera*-samples in Nabaos. On the other hand, below both crowns, an accumulation of C_{org} and N_t was detected, though this was also stronger developed on Gellap.

Again, a species-specific effect is not excluded, although no literature could be found that observed the effects of these species on soil. However, an alternative interpretation is given by the kind of stocking. While on Nabaos, goats and sheep roam, in Gellap sheep are only kept on the parcel of land where the observatory was established (Wolkenhauer, 2003). Also, although Wolkenhauer (2003) stated that sheep were the only livestock type, cows were grazing on the site in 2003 (Gröngröft, 2008, pers. comm.) and during field work in 2004 cow dung was found beneath the *Albicia anthelmintica*-trees in Gellap. In addition to an increased effect by cattle, it may be possible that the three *Albizia*-trees on Gellap are attracting sheep more regularly to rest in their shades than the *Acacia mellifera*-tree on Nabaos, especially, since dense grass patches occurr in direct vicinity and sheep prefer to graze (Brand, 2000, and references therein). On Nabaos, shade is also provided by the much denser and oftenly higher shrub clumps. Grasses are generally missing, and since the *A. mellifera*-individual is the only tree in the surrounding area, it is less likely that this place is favoured by the herd. All in all, these assumptions remain speculative since only one tree unit could be sampled on each farm; however, the effect of the dominant livestock form should be considered a cause of stronger accumulation of nutrients and organic matter under soils of Gellap compared to Nabaos.

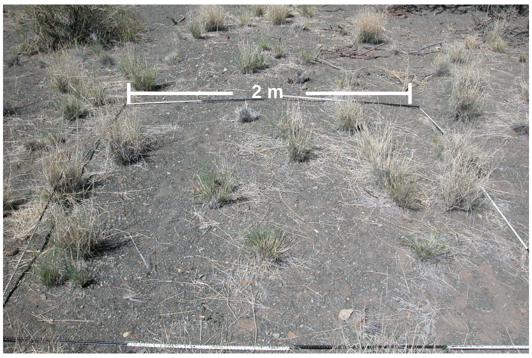


Fig. 5.11: Grass tussocks on Sedimentation Area in Gellap

The comparison of soil next to Grass Tussocks with Open Soil samples showed that grasses contribute to small scale heterogeneity, which supports the considerations of Chapter 5.4.5. The Grass Tussocks occur with interspaces of approx. 30 - 50 cm (see Fig. 5.11). Since an effect on the development of soil patchiness could be shown in at least trends with regard to C_{org}, N_t and C/N-ratio that is on a scale relative to the tussock interspace, the study site "Sedimentation Area" on Gellap is - with regard to the above cited framework of Tongway & Ludwig (1997a) - in a less degraded state than the same study site on Nabaos.

The only occurring physical soil crust on the observed study sites exhibited decreased pH-, EC-, C_{org} -and N_t-values compared to adjacent Open Soil patches. Presumably, on these rather smooth surfaces, runoff is readily generated during rain events and washes small litter particles away quickly. All other surfaces are rather rough and mostly covered with a desert pavement which consists in this case of platty particles in coarse sand size that are derived from weathering of the shist outcrops. The role of these crusts will be further evaluated in Chapter 3.4.

5.4.8 The Influence of Microtopography on Small Scale Soil Variability

Microtopographical structures were far less pronounced on Gellap and Nabaos compared to Soebatsfontein. Heuweltjies and large boulders were missing that increased habitat diversity in Soebatsfontein. Instead, on the wide plains slope inclinations were approximately the same on the study sites with exception of the smooth, low ridges in the Outcrop Areas. But in contrast to Soebatsfontein, shrubs were of considerable height and thus, phytogenic mounds (PGMs) were more frequently and distinctly developed.

In Chapter 5.4.4, it could be shown that plants accumulated N_t, C_{org} and several watersoluble cations and anions in soils within their crown area. Consequently, higher values of EC and wider, in this special case more humus-like, C/N-ratios were found in canopy soils compared to open soils. In addition, the textural composition of soil was altered below shrubs in a way that clay was decreased, while other fine fractions up to middle sand size were increased and coarse sand decreased below shrubs except for the first centimetre, which showed the reverse trend.

It was hypothesised that the height of phytogenic mounds was interrelated to the degree of this fertility island development. Therefore, for each sample location under plant canopies, the relative PGM-height at that particular point was determined by generating several intersections through the DEM. An example of such a terrain section is given in Fig. 5.12.

The PGM height of each miniprofile was correlated with the weighted means of the soil properties over the top ten centimetres of topsoil and the parameter values of the three separate layers. Selected results are presented in Tab. 5.12. The complete list is compiled in the Appendix (Tab. B.12). For all total elements it has to be noted that here only Gellap samples were available; thus, the basis of this analysis was the data of 10 miniprofiles, whereas for

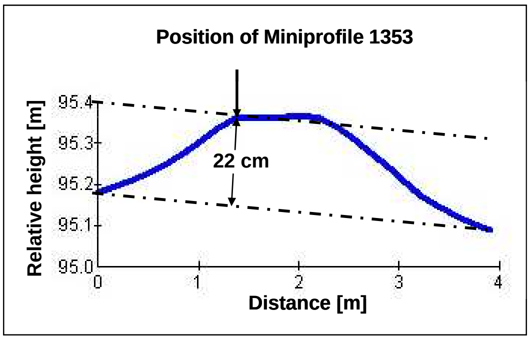


Fig. 5.12: Vertical section through a PGM on the Sedimentation Area in Nabaos.

other soil properties, 30 miniprofiles were included in the analysis.

Parameter	wm 0-10 cm	0-1 cm	1-5 cm	5-10 cm
pH_{H2O}	0.25	**0.47 ***	0.20	0.30
pH_{CaCl2}	0.38	**0.54 ***	0.34	**0.46 ***
$EC_{2.5}$	0.39	0.16	0.38	**0.43 ***
EC_5	**0.44 ***	0.35	**0.44 ***	**0.47 ***
C_{org}	0.14	0.28	0.12	0.35
N_t	0.16	0.20	0.12	**0.40 ***
C/N-ratio	0.11	0.29	0.11	0.30
K_{dl}	-	**0.67 ***	-	-
P_{dl}	-	0.37	-	-
S_t	0.44	0.41	**0.67 ***	0.06
P_t	0.08	**0.73 ***	-0.05	0.14
Mn_t	**-0.67 ***	-0.26	-0.56	-0.52
Ni_t	**-0.66 ***	-0.47	-0.50	-0.27
Sr_t	**-0.72 ***	-0.28	**-0.72 ***	-0.42

Tab. 5.12: Correlation coefficients between soil properties and PGM-height for weighted means over 0-10 cm (wm) and the individual topsoil layers (r > 0.4 highlighted).

All dynamic parameters (pH-values, EC-values, C_{org}, N_t, C/N-ratio, S_t, P_{dl}, K_{dl}) as well as P_t show a positive correlation with the developmental degree of PGMs. The r-values vary in strength between parameters and with depth: while pH- and P_t-values tend to correlate more strongly with PGM-height in the first centimetre, EC-values show stronger correlation in depths. Between C_{org}, N_t C/N-ratio and PGM-height, only low r-values were obtained. For S_t and especially K_{dl}, however, r-values were high.

For total element contents on Gellap sites (apart from P_t and S_t) high correlation coefficients (> 0.4/ < -0.4) were only obtained for negative relationships between PGMs and soil properties. Here again, r-values ranged widely within depth and between the parameters with highest correlations found between PGM-height and Mn_t, Ni_t and Sr_t.

5.4.9 Discussion of the Influence of Microtopography on Small Scale Soil Variability

The analysis of the most distinct microtopographical features occuring in Gellap and Nabaos showed, that the developmental degree of PGMs is clearly related to alterations in soil properties. Coefficients of correlations are rarely higher than 0.5 which indicates that there is a tendency of increased/ decreased parameter values with PGM-height across all sites and all species in the regarded ecosystem but that exceptions of this relation are common. This might be due, for instance, to continuing wash-outs of light organic matter particles on the so-called "Rivier-Island"-locations that are more frequently affected by run-off than other sites. Multiple other factors are conceivable that influence the correlation, which are not quantifyable with the present data set. Perhaps geologically different preconditions on specific outcrops might lead to other soil properties in PGMs in terms of one or several parameters that would not occur in the Sedimentation Areas.

The range in r-values between the three depths may be a result of varying exposition of the sampled PGMs to main wind directions, to species effects (higher susceptibility to wind erosion due to low canopy density) or digging activities of animals. The higher correlation coefficients of EC-values in deeper topsoil layers may be due to rapid leaching of the very dynamic watersoluble salt species. Lower r-values for pH in deeper layers may on the contrary indicate the increasing variability of organic acid production and respiration activity with depth depending on species and stability of the location.

5.4.10 Variability Assessments on the Observatory

Like for the data set taken on the Soebatsfontein Observatory, the variability of soil properties is assessed for the combined data set of Gellap and Nabaos that comprises samples with affiliation to four nested scales (D1-D4) plus depth information (Layer). However, it has to be noted that total element data were only available for the Gellap samples so that calculations upon those parameters are omitted here. On the other hand, as mentioned before, in this landscape, C_{org} and N_t have to be regarded as parameters reflecting geologic conditions as well (see Chapter 5.4.5).

Fig. 5.13 presents the contribution of samples taken on Gellap and Nabaos to total variability of the combined data set. The calculation shows that the differentiation on landscape scale into two D1-groups accounts only little to total variability. An exception is pH_{H2O}, which explains at least 6% of the total variability. This finding may be explained by the formerly described occurrence of calcareous bands in some outcrops in Nabaos and the corresponding pH-differences compared to Gellap (see Chapter 5.4.3).

Also low is the contribution of D2-units to total variability for pH_{H2O}, $EC_{2.5}$ and C_{org}. For N_t, however, D2-units account with 16% to total variability. The shist outcrops found in Gellap and Nabaos have high contents of N and C (Petersen, 2008), therefore, by contrast to Soebatsfontein, N_t and at least to a certain degree C_{org} also represent geologic variability in this data set. As was already discussed in Chapter 5.4.5, N_t is more stable in terms of weathering while C_{org} has more dynamic properties due to the accumulation of organic matter by plants on the one hand, and the assumed destruction of C-species by a still unidentified process during weathering on the other. This might explain the lower degree of explanation by D2, since fluctuations in C_{org} probably have a stronger impact with regard to D3- and D4-units that determine the degree of open soil patches and with that the exposition of soil to the possible destructive

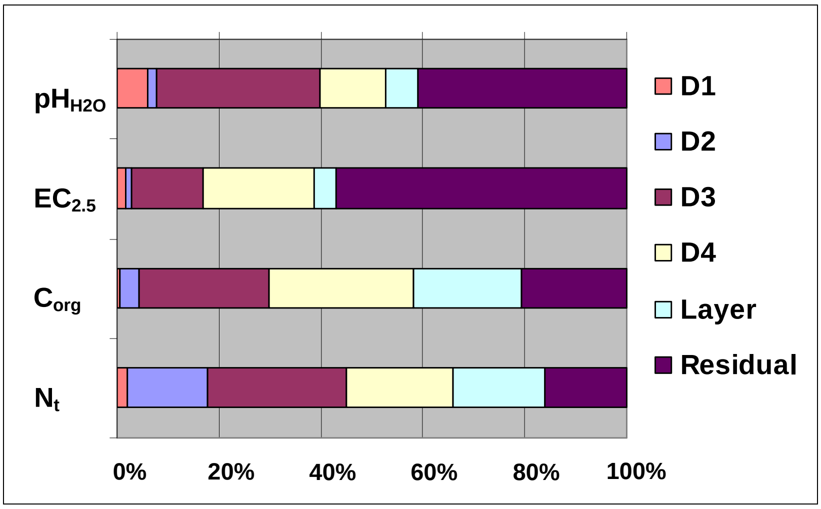


Fig. 5.13: Variability contribution of D2-units (here separated into Sedimentation Areas (SE) and Outcrop Areas (OC)) to total variability of the combined Gellap/ Nabaos data set.

force of radiation. These patterns occur within D2-units but not inbetween: open soil/ non-open soil patches occur on both, Sedimentation and Outcrop Areas.

Concerning all parameters, D3 contributes strongly to total variability, ranging between 14 and 32%. The structuring into units with less weathered outcrop ridges of various kind (bulky and fine structured shists), units with more strongly weathered and mixed materials and units being affected to different degrees by hydrology (Rivier- and Rivier-island units) accounts for strong variability explanation.

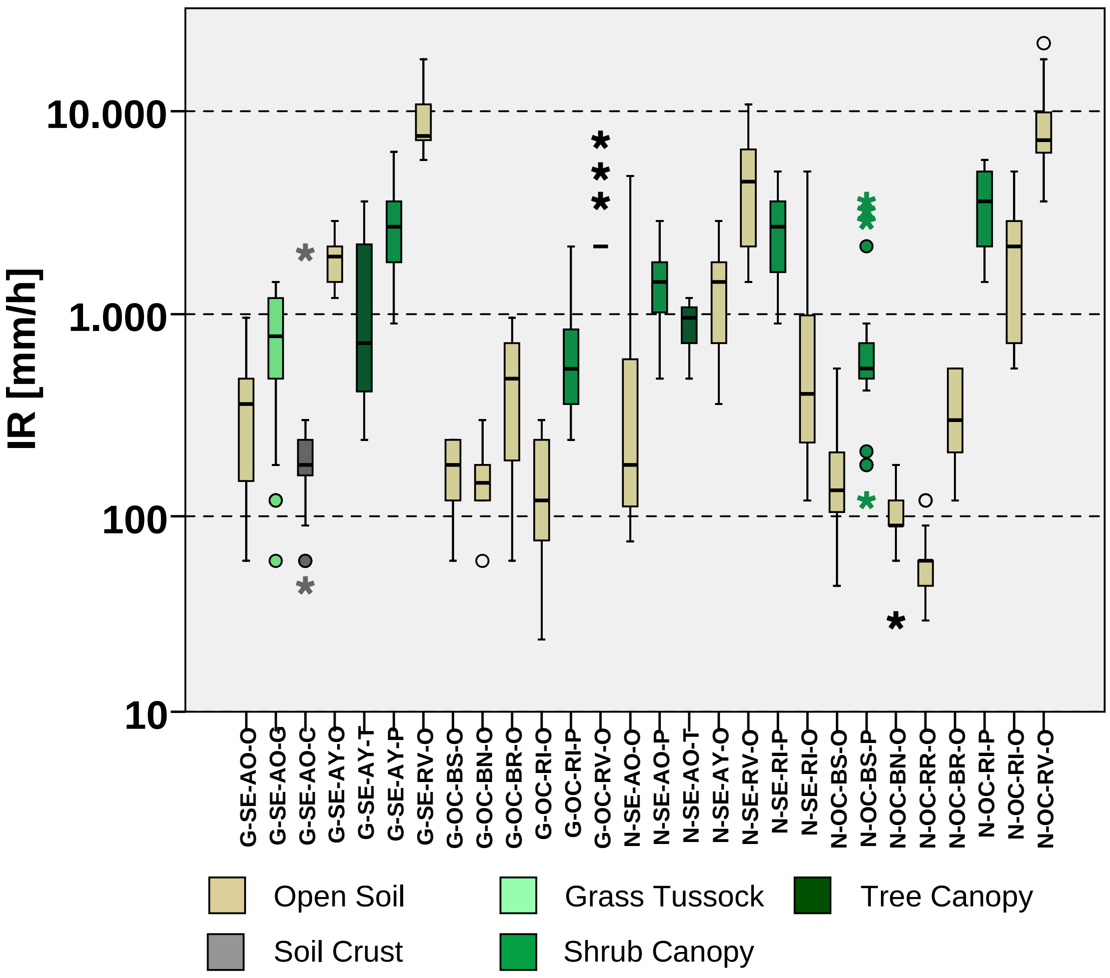
Also high is the impact of D4-patterns on total variability for all parameters. This is mainly due to the differentiation into samples of Open Soil and Canopy Soil-units that affects pH$_{H2O}$, EC$_{2.5}$, C$_{org}$ and N$_t$ alike.

The Layer-factor contributes most strongly to variability in terms of C$_{org}$ and N$_t$ since these parameters show the strongest gradients with depth on Canopy sites. Moreover, the proposed destruction of (geogen) C$_{org}$ by radiation is strongest on top layers of Open Soil.

5.4.11 Hydrology

5.4.11.1 Infiltration Rates

On 28 D4-units on both observatories, single ring infiltration tests were conducted according to the procedure described in 2.2.6. An overview of the results is provided in Fig. 5.14.



n	Min.	Perc. 25	Median	Mean	Perc. 75	Max.	SD
153	24	180	720	1592	2160	21,600	2,438

Fig. 5.14: Overview of single ring infiltration rates of different D4-units on the observatories Gellap and Nabaos.

Infiltration rates were at times highly variable with an increasing variability on high-infiltration sites. Values ranged between 24 and 21,600 mm/h, with a mean of 1,600 mm/h, a standard deviation of 2,400 mm/h and a median of 700 mm/h. The data distribution is strongly controlled by extremely high values of Rivier-units.

Apart from the Rivier-units, which had basically unlimited infiltration rates with regard to the applied method, highest values were obtained for Shrub Canopy sites and in most cases Rivier Island sites. Lowest infiltration rates were found on the crust site and the Open Soil sites of the Brown and Red Ridges as well as on the Rivier-Island unit of Gellap. Remarkable is the high deviation of infiltration rates for Rivier Island D3-units. On the two comparable study sites "Sedimentation Area", it could be shown that infiltration rates increase with increasing age of the sediments in the row Old Accumulation < Young Accumulation < Rivier. Variabilities of infiltration rates are still very high, although not significant, the described trends are clear. No differences occur between sites of Gellap and Nabaos.

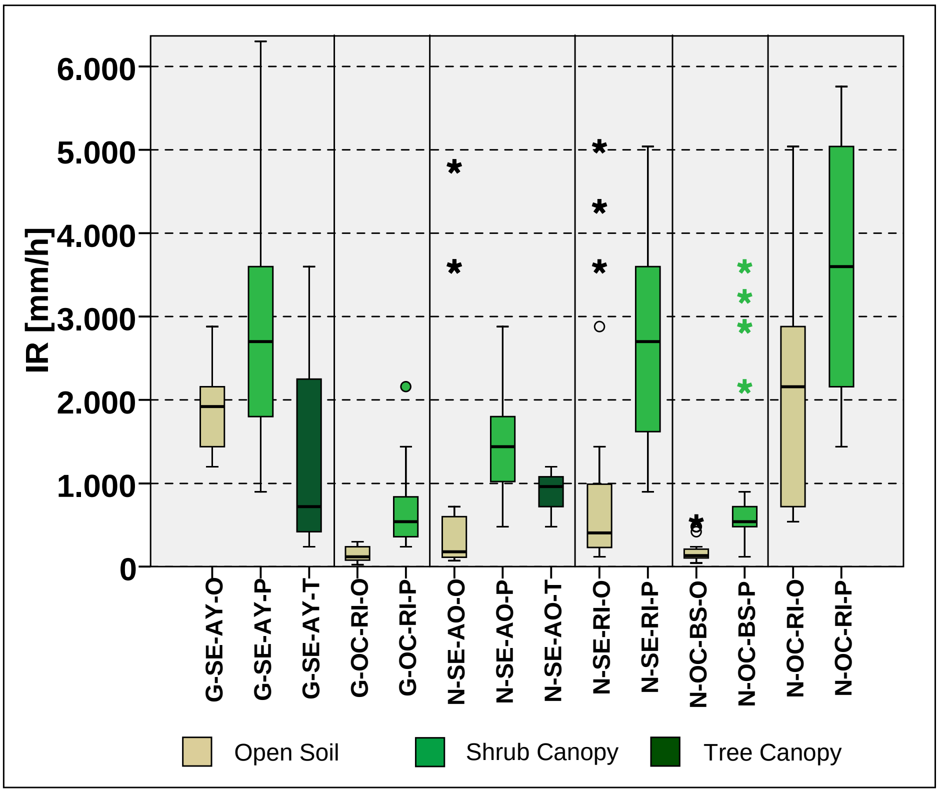


Fig. 5.15: Overview of single ring infiltration rates of Open Soil (O)/ Shrub Canopy (P)-units on the observatories Gellap and Nabaos.

In Fig. 5.15, the results for a direct comparison of Shrub Canopy (P) and corresponding Open Soil (O) test sites are summarised. Here again, the high variability of the results leads to negative significance tests; however, the following tendencies are obvious: tests conducted below shrub canopies result in clearly higher infiltration rates than those conducted on Open Soil patches. This trend is valid for all six data pairs. In addition, the two trees exhibit lower infiltration rates compared to Shrub Canopies in both cases but not compared to the corresponding Open Soil units. Based on the mean value of each data distribution, the location below shrubs increased the infiltration rate in comparison to adjacent open soil with a factor ranging between 1.5 and 8.0.

In a next step, it was tested whether the detected differences were correlated to texture effects of the topsoil. For this purpose, texture analyses of the layer 1 - 5 was used since the loose coarse sand cover on top of the soil surface was removed prior to the infiltration test. Highest negative correlations between the logarithmized infiltration rates and texture classes were obtained for clay (r = -0.66), cSi (r = -0.61) and the sum of both fractions (r = -0.77). Highest positive correlations occurred for middle Sand (r = 0.58), (r = 0.53) and the sum of these (r = 0.70) (Fig. 5.16).

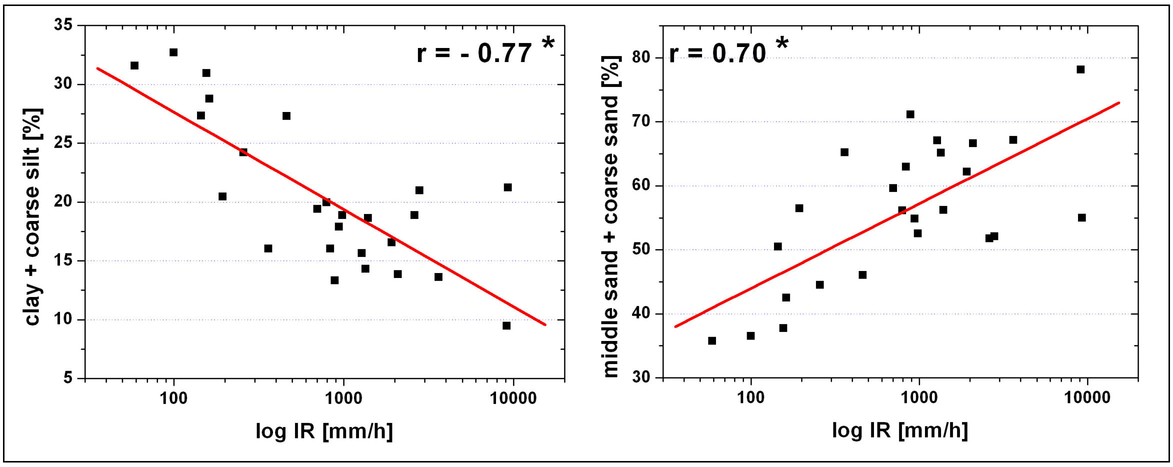


Fig. 5.16: Correlations of infiltration rate and selected texture classes.

Another correlation was deduced between the logarithmised median infiltration rates of the six Open Soil units of each Shrub Canopy/ Open Soil data pair and the factor between the Open Soil infiltration rate and the increased value below shrubs (see Tab. 5.13). A linear relation was observed with r = 0.79. This correlation indicates that infiltration rates are more strongly increased by plants on the sites that have relatively low infiltration rates.

With this finding, it is possible to predict infiltration rates below Shrub Canopies for D3-sites where infiltration tests of Open Soil D4-units were conducted. This extrapolation was conducted for the unit GE-SE-AO, where infiltration rates were only measured on Open Soil, but not below shrubs.

D4-Site	**Median IR of Open Soil [mm/h]**	**Median IR of Soil under Shrub Canopy [mm/h]**	**Factor between IR of P and O**
GE-SE-AY	1800	2700	1.5
GE-OC-RI	120	540	4.5
NA-SE-AO	180	1440	8.0
NA-SE-RI	405	2700	6.7
NA-OC-BS	135	540	4.0
NA-OC-RI	2160	3600	1.7
GE-SE-AO	375	**2002**	**5.3**

Tab. 5.13: Median infiltration rates and factor between Shrub Canopy/ Open Soil data pairs in Gellap and Nabaos. In bold: extrapolated value (explanation see Chapter 5.4.11.1).

5.4.11.2 Topsoil Water Contents after Rain Event

After a rain event in the night from 24 to 25 March 2005 on the small scale study site "Sedimentation Area" on Gellap (G-SE), the water content of topsoils was determined for selected D4-units. According to the BIOTA weather data (www.biota-africa.org), 5.4 mm precipitation fell. However, personal observations assume higher precipitation amounts of about 25 mm. The results of topsoil water contents confirm this assumption and are presented as box-and-whisker plots in Fig. 5.17 [8].

All Open Soil units of the D3-sites Older Accumulation (G-SE-AO-O), Younger Accumulation (G-SE-AY-O) and Rivier (G-SE-RV-O) stored the same water contents of approx. 24 mm. It is suggested that this is the actual amount of precipitation. The Crust- (G-SE-AO-C), Plant Canopy (G-SE-AO-P) and Tree Canopy (G-SE-AY-T) unit had less mm water content in their topsoils, with the Crust site having lowest values with a mean of approx. 7 mm. Grassy plots, however, exhibited increased water contents.

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[8] The value indicated by * was derived from an extrapolation of IR-values of the corresponding Open Soil site and a correlation of factors of IR-increase under Shrub Canopies compared to Open Soil units (expl. see text).

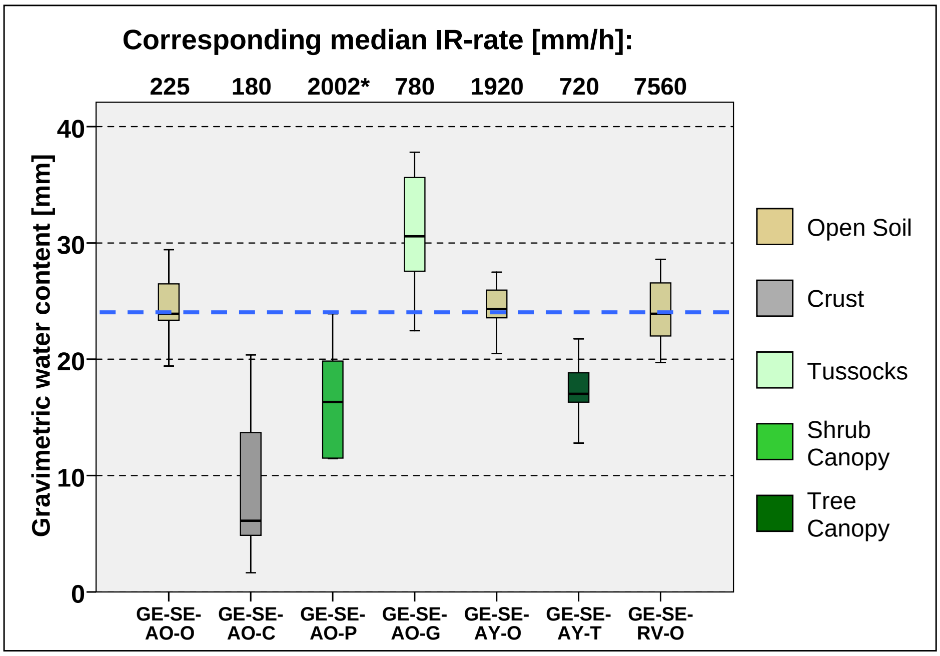

Fig. 5.17: Topsoil water contents in Gellap after a rain event in the night from 24 to 25/03/2005. The dashed blue line indicates the amount of precipitation. * indicates an extrapolated IR-value (explanation see Chapter 5.4.11.1.)

5.4.12 Discussion of Hydrology

Infiltration generally increased with decreasing age of the sediments with regard to the Sedimentation Areas. The assumption that infiltration rates were correlated with particular texture species was tested and indeed, relations could be found between mean infiltration rates and the amount of coarse silt, very fine sand, coarse fine sand and total fine sand. These findings are to some extent in line with the observations of Mills *et al.* (2006) who tested the predictability of infiltrability from texture data. Infiltration rates in this study were determined by using a laboratory method developed by Mills & Fey (2004a). The authors found good relations with water-dispersible silt (r^2 =0.96), water-dispersible clay (r^2 =0.88), very fine sand (r^2 =0.86) and medium sand (r^2 =0.84) and interpretated the role of texture as either blocking pores or shaping them. Coarse particle fractions were attributed to have a sceletal function within soil, while fine particle fractions have a plasmic role. The authors assume a switch from sceletal to plasmic role at a particle size of approximately 0.1 mm, which matches the transition from the particle fractions finest fine sand and coarse fine sand with regard to the present study.

The present study methods deviated from the investigations of Mills *et al.* (2006) as described in the following:

- in the present study, a field method was applied that was not of high precision but had its strength in terms of applicability and relative comparability
- test sites and miniprofile plots did not match in location. The comparison was based on the affiliation with the same D4-unit
- texture data was derived from composite samples of five miniprofiles of the same D4-unit
- in the present study, water dispersible texture fractions were not specifically determined

Despite these differences, the obtained results are to some extent comparable with the finding of Mills *et al.* (2006). When regarding coefficients of correlation in the 1-5 cm layer, a switch from negative r-values to positive r-values is given at particle size fraction finest fine sand (particle size 0.063 - 0.125 mm) (See Appendix, Tab. B.11). For the next fraction on the scale, coarse fine sand, no correlations occured and from middle sand size onwards, positive correlations were obtained. These findings confirm the suggested function of plasmic and sceletal fractions in soil. The results further confirm the applicability of single ring infiltration tests despite their comparably high inaccuracy. The method applied is a simple field test and the relatively high susceptibility to errors had been countered with increasing the number of measurements. The largest source of inaccuracy is probably the overestimation of the infiltration rate due to the small test area (with a diameter of 12.5 cm) and the relatively high degree of radial water discharge below the surface. Therefore, absolute infiltration values obtained in this manner are certainly not applicable for particular issues as for instance the determination of threshold values of rain events that result in run-off generation. Nevertheless, the comparability with the findings of Mills *et al.* (2006) shows that the method is appropriate as a relative measure to compare micropatch units. The methodological strength is the creation of a larga data set which is required for the characterisation and delineation of strata and when only low amounts of water are available, as is normally in dryland studies. The alternative with higher accuracy is rainfall simulation that needs hundreds of litres of water for observations on single plots and are therefore not applicable for the purpose of the present study.

However, the statistical significance of data derived by this method is often not given due to the high variability of single ring infiltration tests on the different units. This is not due to the test itself though, but rather a matter of topsoil patchiness. This becomes evident when regarding the high degree of reproducibility of single tests: Fig. 5.18 compares IR-measurements on several replicate plots (different colours) and of several replicate measurements within same infiltration rings. The latter is represented by a zigzag course of the same coloured line in which each increase represents the repeated fill-up of a ring. The slopes of each measurement within the same ring after fill-up is largely similar; the curves of the different plots are also very similar, although some curves already indicate the variability of results between replicate plots.

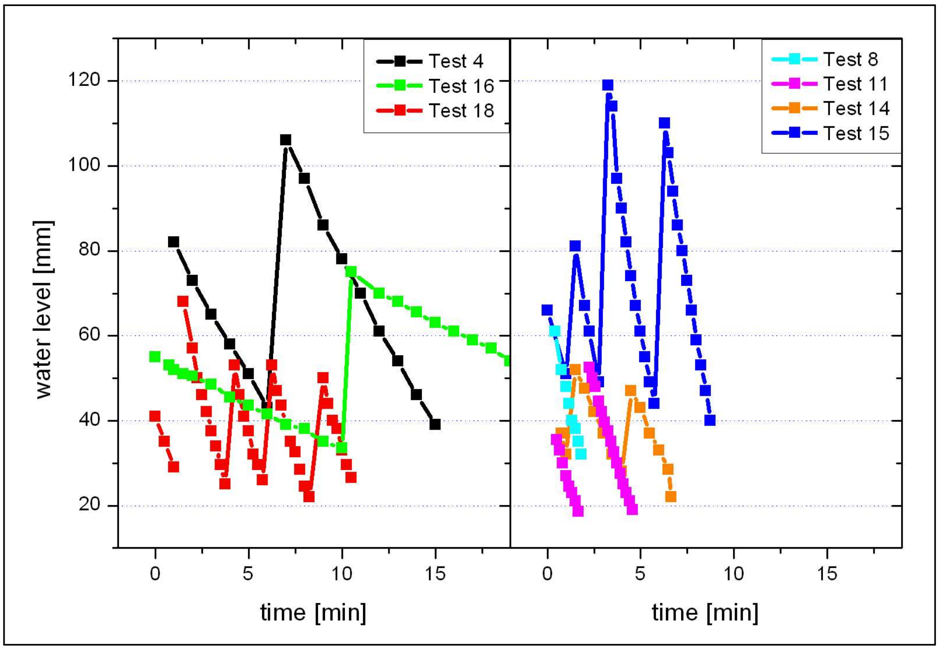

Fig. 5.18: Comparison of infiltration tests exemplary for D4-unit "Tussock" on the Older Accumulation Area on Gellap (G-SE-AO-G). Further explanations see text.

Below shrub canopies, higher infiltration values were found in all cases where Plant and Open Soil units were compared. This is also explainable with textural differences between these two D4-units (compare Tab. 5.7). Regarding the texture analysis of the layer 1-5 cm again, significantly decreased values were obtained below shrubs for clay. On the other hand, in this layer, medium sand was significantly increased. These two differing fractions match perfectly those fractions with high coefficients of correlation with infiltration rates. For coarse sand, however, a significant increase in soils below shrubs would have been expected as well but was not found, and for coarse silt the finding was even controversial to the correlation. As an explanation for this, it has to be considered that texture data was not derived from infiltration plots directly, but from composite samples of miniprofiles that had the same D4-affiliation.

But even if the significantly increased values of coarse silt should actually result in decreasing infiltration rates, other parameters have been reported as infiltration increasing agents which might interfere with texture effects: in previous studies, a relationship between infiltration rates and the amount of humus, clay mineral composition, pH, electrolyte concentration and exchangeable cation composition were found. Some of these constituents, organic carbon, calcium and iron oxides, reduce the tendency of soils to crust because they stabilise the soil by antagonising the dispersion of fine particles through raindrop impact (Mills & Fey, 2004b, 2003b). Since it could be shown that organic carbon was increased below shrubs compared to open soil, this soil property may even add to texture effects and further increase the infiltration rate (Tab. 5.8 and Tab. 5.9. The same might be valid for bivalent cations Ca_{we} and Mg_{we}, though the increased values under shrub canopies were not significant.

On summary, the increased infiltration values found below shrubs are presumably a result of various factors the most important ones of which are: a reduced amount of fine particles, especially coarse silt and clay, that have a plasmic function in the soil, an increased amount of the fractions medium and coarse sand that act as sceletal components in soil, the increased amount of aggregate stabilising agents, in this case bivalent cations and organic carbon, and, finally, probably the shielding effect of the plant crowns that protect the soil surface against the dispersional effect of rain splash.

Another interesting aspect of the infiltration tests arises from the comparison with topsoil water contents after a rain event. The three Open Soil units on the test site represent sediment depositions that ranges in age in the order Old Accumulation (AO) > Young Accumulation (AY) > Rivier (RV). Infiltration rates increase in the same row, while water contents after a 25 mm rain event are the same on the three units. This indicates that infiltration capacity of these units is not limiting the uptake of water, at least not at a rain event as occurred on the 24 to 25 March 2005. The exact amount of precipitation in timely resolution is of crucial importance for the evaluation of the infiltration rates and their ecosystematic role. This however, is not quantifyable since the BIOTA weather data only shows a rain amount of 5.4 mm for the whole night, which implies either a malfunction of the rain gauge or a high variability of the rainfall patterns within short distances. Therefore, a statement upon the relation of threshold infiltration rates for a certain rain intensity cannot be provided at this point. However, for this specific rain event of 24 mm on Gellap, it can be stated that an effect occurred on the crust site with its relatively decreased infiltration rate of 180 mm/h since obviously not all water could infiltrate and run-off was generated.

Other units show reduced water contents compared to the Open Soil units (Fig. 5.17). Those are the Crust site, a site under a shrub on the old Accumulation Area and a site below the canopy of a tree in the D3-unit "Younger Accumulation". The test sites under plant canopies stored less water compared to the Open Soil units because of the shielding effects of the canopies. Further it can be concluded, that the rain intensity was too weak to generate runoff that would result in higher topsoil water contents below the plants. On the other hand, the low water contents of the Crust site result from the sealing effect of the physical soil crust that must have resulted into some runoff or a higher water content would be expected. This corresponds with the lowest infiltration rates obtained for this unit.

A last group showed increased topsoil water contents compared to Open Soil units in samples taken in direct vicinity to grass tussocks. The water accumulation is interpreted as a result of interception effects by the funnel-like shape of the tussock that direct the trapped raindrops to the centre of each plant and thus enhance water storage in the rooting zone.

The nature and functioning of grass-tree interactions in savannas has widely been discussed (Rodríguez-Iturbe & Porporato, 2004; Scholes & Walker, 1993; Hipondoka *et al.*, 2003). Ecohydrology is regarded as the main factor controlling the co-existence of grasses and trees or shrubs. Although the Nama Karoo is a special kind of a savanna, the theoretical background applies here as well. Two types of models exist that either assume that savannas are in a state of equilibrium or disequilibrium. Equilibrium models are niche separation and balanced competition models, of which the first postulates that competitors avoid competition by using qualitatively, spatially or timely different resources while the second assumes that an interspecific competition exists which is subsidiary, however, to intraspecific competition. Disequilibrium models regard savannas as not stable. The fact that savannas persist is regarded as the result of frequent changes in the environment (for example fire or herbivores) that prevent the extinction of either competitor or biasing it alternately toward one or another competitor (Scholes & Archer, 1997).

The efficient water collection during rain events observed for grasses in the above-described experiment suggests that grasses are not capable of exploiting water resources of deep soil layers to the same degree as woody plants are. Therefore, their survival strategy dictates them to intensively trap rainwater, to quickly respond to rain events by intensively using topsoil water and rapidly fulfilling their life cycles. When topsoil water is used up, the outer parts of the plants die off and a well hidden live core part persists during the dry season. In-between, shrubs use water storages of deeper soil layers which they may have facilitated by stemflow.

6 Concluding Discussion on Scale-Dependent Processes in Southern African Drylands

6.1 Introduction

In the preceding chapters, the variability of topsoil properties was described with regard to landscape units of different scales, different parameter groups and two different biomes, whereas main focus was placed on small- and meso-scale features. In this chapter, it is attempted to deduce a more holistic understanding of scale-dependent processes and their interactions in drylands. For this purpose, processes are identified on the micro- and the meso-scale, and later linked to large scale impacts. In conclusion of this chapter, the implications for further research and future challenges in the management of drylands are outlined.

6.2 Processes on the Microscale (D4 = dm^2 - m^2)

The literature review and the findings from observations in the Succulent Karoo and Nama Karoo revealed multiple interactions between topsoil patterns and micro-features of the so-called D4-scale. To visualise potential processes behind these interactions, a scheme is presented showing the D4 units in an idealised dryland ecosystem (Fig. 6.1).

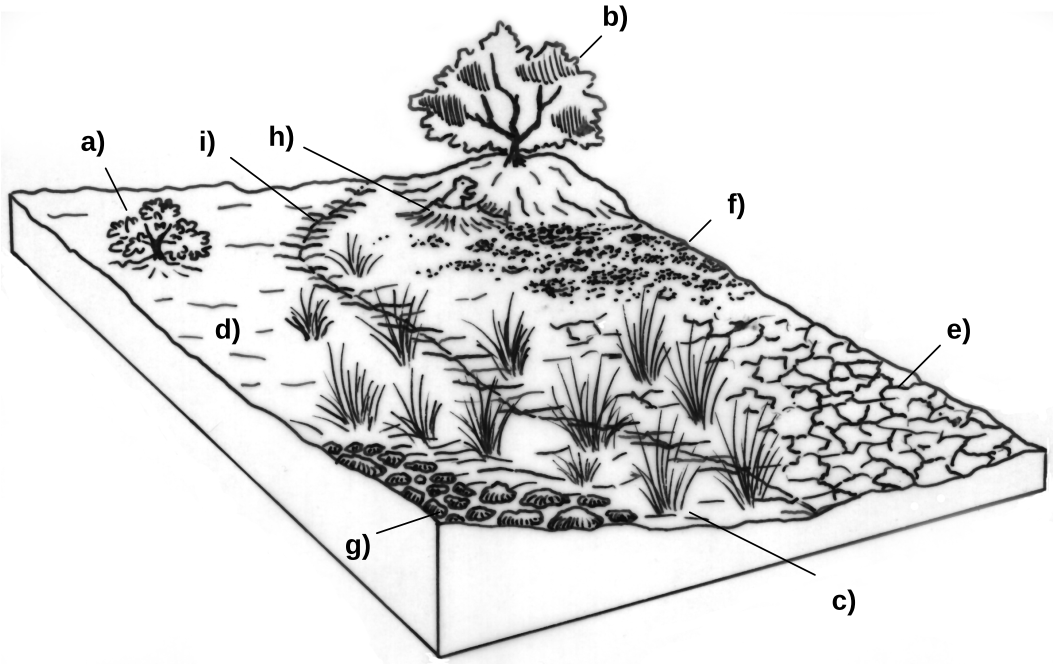

Fig. 6.1: Scheme of D4-patches in an idealised dryland landscape. Explanations see text.

Most striking micro-structures of semi-arid landscapes are created by vegetation, be it dwarf-shrubs (a), as occur in the Succulent Karoo, larger shrubs (b) as for instance the species *Catophractes alexandrii* or *Boscia foetida* typical in the Nama Karoo, or tussock grasses (c) which are a structural component of savannas and found on the Gellap study site. Plant patches in either form typically alternate in drylands with open soil patches (d). However, apart from a ”typical” open soil patch, special characteristics may occur on such areas that in turn make up own structural units exhibiting different influences on soil properties. Those are mineral (e) or biological soil crusts (f) and pebble covered (g) areas, for instance so-called ”desert pavements” (Gellap/ Nabaos) or quartz fields (Soebatsfontein). All of these structural units may be further superimposed by disturbance spots (h) caused by digging mammals, insects or through trampling, and by microtopographic alterations of depressions and elevations that dictate the run-off courses (i) in case of excessive rain events.

Part of the soil variability could be explained by affiliation with different D4-units, which could be shown by ANOVA-results. This variability applied in different degrees to the parameter groups analysed: it is concluded that the observed topsoil patterns are generated by underlying processes that are in turn linked to particular micro-features. Therefore, the variability of topsoil properties is regarded as an indicator for processes occuring in the ecosystem on the D4-scale.

Processes were found that could be interpreted as having either an increasing or homogenising effect on the variability of soil properties. Often, effects appeared for only particular parameter groups while others behaved rather immanently. This often proved to be dependent on the dynamic of the property groups whereas the analysed parameters appeared to be less dynamic in the following row:

temperature > hydrologic parameters (water content, infiltration) > watersoluble ions and EC > plant available nutrients (K_{dl}, P_{dl}) > organic matter related properties (C_{org}, N_t, C/N-ratio) > total contents of other elements

Furthermore, it could be deduced from the findings of this study that some micro-scale processes had quite an increasing or - to the contrary - homogenising effect on the patchiness of soil properties.

Against the background of these assumptions, the observed processes are discussed in detail in the following and their validation is underlined by examples from the Succulent Karoo (Soebatsfontein) and the Nama Karoo (Gellap/ Nabaos).

Small Scale Distribution of Water This process complex comprises of several factors and processes that in their combination lead to patchiness of water in drylands. The determination of the fate of precious rain water starts with the impact of raindrops on the landscape surface. Where plants occur, the rain drops impinge on leaves first and the force with which they contact the soil is reduced. In semi-arid environments, however, open soil patches are a typical structural element of the ecosystems. Here, rain drops impact on soil particles with full strength, which may lead to the dispersion of clay and silt, a slaking of the soil surface, pore clogging and, finally, the formation of mineral soil crusts. The extent of crust formation depends on several soil factors, which are summarised by Francis *et al.* (2007). They include clay mineral composition, pH, electrolyte concentration, exchangeable cation composition and soil organic matter content, whereas humus, calcium and iron oxides act as stabilising constituents that reduce the tendency of soils to crust. Soil crusting in turn effects the infiltration capacity of soils. Therefore, raindrop impact and soil crusting trigger a patchiness in terms of higher infiltration rates below plant canopies where raindrop impact is reduced, and potentially lower infiltration rates on patches with mineral soil crusts.

This effect could be demonstrated on Gellap and Nabaos study sites where single ring infiltration rates measured under seven plant canopies and adjacent open soil patches on six different D3-sites revealed an increase of infiltration rate below canopies in all cases, ranging between factor 1.5 and factor 8 (Chapter 5.4.11.1).

The patchiness in terms of high and low infiltration areas has to be further interpreted as the structuring of the small-scale landscape into run-off and run-on zones which determines the optimal storage and use of resources such as water and nutrients. A demonstrative example for the relation of infiltration rate and distribution of water in topsoils after rain events could be provided for Gellap (Chapter 5.4.11.2) although the soil properties of this landscape are not favourable for toposoil crusting due to the kind of texture found here. The demonstrated effects on the Soebatsfontein site were less relevant, since the observed rain events, which were indeed typical for the winter rainfall regime, were too weak to result into run-off.

On summary, the patchiness of water content after rain is controlled by variability of infiltration rates between D4-units, rain intensity and D4-patch sizes. The discussed factors contributing to the process of small scale distribution of available water in drylands may be interpreted as a predominantly variability increasing process. On the other hand, it also acts as an homogenising agent when e. g. considering the redistribution of water-soluble ions from zones of concentrations (for instance former plant sites or disturbance patches due to digging activities of animals).

Distribution of Water-Soluble Ions In drylands, the distribution of water soluble ions proved to be very patchy, as could be shown by own investigations. The patchiness is increased by the spatial constancy of one-way soil water movements, for instance as a result of irregular infiltration rates or root uptake. On the other hand, a permanent change in soil water flow direction leads to a decrease in the variability of ions as well as simple diffusion processes in wet soils. Parameters that indicate these processes are watersoluble cations and anions as well as the related parameter EC. It has to be noted that the process may have two different implications for ecosystems: certain water soluble species are nutrients such as NO_{3we} or Ca_{we}; an increase of these parameters therefore has often to be regarded as desirable, like for instance, for the sites in Gellap and Nabaos where generally low EC-mean-values of 50 μS/cm on Nabaos and 90 μS/cm for Gellap indicate the paucity of the ecosystem. The slight but significantly increased EC-values and also NO_{3we} values that could be detected for the less degraded, commercially managed Gellap site, verify this assumption. However, an increase of EC and watersoluble ions may also be disadvantageous when EC-values increase beyond a threshold of approximately 1000 μS/cm in 1:2.5 water-extract and more osmotic and toxic effects on vegetation become increasingly possible. This, admittedly, depends on the kind of plant species and the texture of the particular soil. Also, particular ion species have to be regarded as nutrients, while others, namely Cl_{we}, have to be regarded exclusively in their role as determinants of osmotic potential and salt stress. Even if the osmotic stress is still low at this value, the increase in osmotic pressure with drying of the soils may reduce water availability near the wilting point and thus affects the water balance of non-adapted plants.

The analysis of water soluble ions on a D4-scale led to a high variability in the mentioned parameters *within* D4-units, which resulted in terms of EC-values, as the representative parameter for the whole group of highly soluble species, in a high percentage of residual variances within all ANOVA-applications. In other cases, significant differences *between* D4-units could be observed. Plants show the tendency to increased EC-values in comparison to adjacent open soil patches. This was confirmed for canopy/ open soil comparisons on Nabaos, and - though not significant - for some D3-sites located in the Mountain Top area in Soebatsfontein. However, for Gellap and other plant sites in Soebatsfontein, the process could not be confirmed and it is questionable, whether the effect is species specific.

The highest variability increase due to redistribution of water-soluble species was observed on the Western Slope Matrix site in Soebatsfontein. Here, inclined areas covered with BSC and plants alterated on the small scale with more level, open soil patches, leading to a strong differentiation in EC-values between the D4-units: while BSC-samples had a mean EC-value of 35 - 61 μS/cm, open soil samples showed the 30fold values with mean values ranging between 1450 and 1780 μS/cm in the three layers.

Other examples indicate that directional soil water flow patterns are a typical phenomenon of drylands. In case of salt imports on the D3-scale (Soebatsfontein, Western Slope Matrix), strong differentiation on the D4-scale (with 30fold increased EC-values on planar open soil patches compared to inclined plant and BSC patches) indicate the temporal stability these processes can obtain.

Humus and Nutrient Accumulation and Organic Matter Decomposition

Frequently discussed at points in this thesis was the occurrence of so-called islands of fertility. This term is used for the accumulation of C_{org}, N_t and varying kinds of nutrients below shrubs in arid and semi-arid ecosystems. The development of fertility islands is described by Hook *et al.* (1991): litter fall leads to the accumulation of organic matter below the crowns of shrubs and trees. The redistribution of topsoil material by wind and water erosion and the trapping below canopies increase this effect. In addition, nutrients are taken up by roots from inter canopy areas, are accumulated in tissues and deposited again as litter beneath the plants. Animals seeking shelter under plants contribute to the fertility island formation by leaving behind their excrements and unconsumed food components.

The accumulation of organic matter and nutrients indicated by C_{org} and N_t was evident under plant canopies of Soebatsfontein, Gellap and Nabaos. In Soebatsfontein, this effect applied to the predominantly occurring dwarf shrubs on the first centimetre of soil; in deeper layers the effect receded and even tended to reverse. In Gellap and Nabaos, however, the accumulation of C_{org} and N_t was significant in all cases but one. Additionally, in most cases accumulations of further nutrients could be identified as was already discussed in Paragraph 6.2.

The decomposition of organic matter is a permanent effect which counteracts the variability-increasing effect on humus accumulation but at the same time increases the variability in terms of nutrients that are set free during this process (e.g. NO_{3we}). Usually, organic matter accumulation and decomposition are in balance at a certain climax stadium, for instance in the case of a fully developed fertility island. Therefore, although in this case organic matter decomposition has to be regarded as a homogenising process in terms of C_{org} and N_t, it will have little effect on the already existing variability between canopy and open soil. The homogenising effect becomes more obvious when considering the example of so-called "ghost islands" (Halvorson *et al.*, 1997). Those are former fertility islands where plants have died away and underwent a process of decay. In some cases, accumulations are still detectable after up to 10 years (Halvorson *et al.*, 1997), although morphological evidence of the formerly living plant is long since missing. Nonetheless, these ghost islands are bound to be completely decomposed at some point in time, which underlines the homogenising effect of this process. Neither on Soebatsfontein nor on Gellap and Nabaos ghost islands were detected. However, the increased values of C_{org} and N_t below dead shrubs that exceeded those of plant canopy soil samples, indicate the effect that these patches most likely have on soil variability even after years of decay.

Establishment of Biological Soil Crusts A lot of publications exist regarding BSC and their role in ecosystems (see Chapter 3.3.7 and 3.4). BSC occurred on Soebatsfontein and were thoroughly observed with regard to commonly assumed interactions with topsoil properties. Basically, BSC were attributed with the following effects:

- they increase pH-values (Büdel *et al.*, 2004; Garcia-Pichel & Belnap, 1996)
- they are important suppliers of N in the otherwise N-depleted drylands due to their N-fixing ability (Belnap, 2001)
- they contribute to C-content in soils (Evans & Lange, 2001)
- they increase nutrient availability (Harper & Belnap, 2001)
- they bind dust particles on the surface through dust trapping (Blank *et al.*, 2001)
- they influence the infiltration of rain water into the soil (Warren, 2001b)

The findings of this study could confirm the observations of other research groups to some extent but also, certain parameter groups failed to verify expectations. In terms of pH, on practically all of the study sites increases on BSC-sites relative to adjacent open soil sites could be detected, although these sites were located on strongly differing parent materials, ranging from calcareous heuweltjie substrates to lower-pH matrix units of the slopes. Also in line with literature were the observations that BSC sites had higher amounts of silt particles in the upper topsoil layer compared to adjacent open soils, which corresponded also to increased total contents of particular elements such as Mn_t, Al_t, Ti_t, Fe_t and Zn_t. Concerning the influence on infiltration rates, it could be shown that BSC-sites were always among those sites with the lowest infiltration rates and exhibited in most cases lower infiltration rates than adjacent open soil sites (Chapter 4.4.11.2).

Expectations that were not clearly met in the present study concern the increased values of N, C and nutrients, the latter expressed by the parameter EC. N_t and C_{org} showed strongly inconsistent trends with in parts increased, decreased or equal values on BSC and adjacent open soil sites. K_{dl} showed no differences in a combined data set, and P_{dl}-values were even significantly decreased on BSC-sites on a $p < 0.1$ significance level. EC-values were in one of six cases increased, otherwised decreased on BSC-sites, and NO_{3we}-contents were always lower on BSC-sites. On the other hand, C/N-ratios showed in all cases lower values on BSC-sites.

The findings were attributed to the following reasons:

- The precondition for the establishment of BSCs is a stabilised soil surface. Therefore, BSC occur on sites that are more strongly leached, which explains the lower EC-values in most cases
- Because open patches in general are intruded by roots from the surrounding plants, a fact which is amplified by the stability of soils, plants may probably extend fine roots to areas below BSC and directly consume nutrients such as NO_{3we} and P_{dl} at the place of fixation/ availability
- nutrients may be readily leached and redistributed amongst the boundaries of analysed D4-units

Generally, BSC occurrence may promote different processes under varying scenarios of ecosystem states: in an undegraded system, BSC increase the patchiness of water availability and thus increase the stability of plant communities. In a degraded system, BSC may a) disappear, for instance due to the combined effect of trampling and erosion; in this case, patchiness is reduced; or b), BSC occurrence may on the contrary increase due to reduced vegetation and subsequent crusting which leads to an increase of BSC patch size that may result in higher run-off amounts and subsequent resource losses for the ecosystem.

With regard to the soil properties that showed detectable differences between open soil and BSC, the process of BSC establishment has to be evaluated as variability increasing on the D4-scale. With regard to the other parameters, for instance input of N into the ecosystem by N-fixation, an effect of BSC is most probable, although it was not verified by means of a comparative analysis of open and BSC encrusted topsoil on a D4-scale. Here it is suggested that nutrients are redistributed across the relevant scale; consequently, the effect is rather homogenising in terms of D4-patterns.

Bioturbation and Trampling Bioturbation and trampling are processes that lead to disturbances of the soil. The degree of disturbance may range from small digging holes of ants that lead to increased infiltration rates in an otherwise encrusted D4-patch, to large disturbance patches of *Aardvarks* (several m^2, up to one m depth) that are frequently found in heuweltjie centres. The latter does not only strongly alter soil properties *in situ* but also in the surrounding area, where excavation material is deposited to some extent after short-distance translocation by wind and water.

In the short term, bioturbation and trampling increases the variability of topsoil properties, as could be shown on Soebatsfontein, where a couple of mole mounds led to a strong increase of variability within a D4-unit. But in the long run, the effect is homogenising, which should not be underestimated in its role for ecosystem stability. As an examplifying example, reference may be made to the work of Constanze Grohmann, who currently analyses the bioturbating effect of the termite species *Macrotermes michaelseni* in central Namibia. The author estimates a soil turnover by mound construction and decay of approx. 20 kg ha^{-1} a^{-1} (pers. comm.). This estimation, however, has to be regarded as a first, rather rough approach due to the high variability between different mounds and different rain intensities. Nonetheless, the amount of sheeting materials that undoubtedly also contributes to turnover by termites, has to be added to the estimation and will probably exceed turnover rates derived by mound materials only. In any case, this has a strong implication for the juvenilisation and the maintenance of soil fertility. The same function may be fulfilled by other soil dwellers such as ants or digging mammals.

Wind Erosion and Wind Accumulation The effects of wind erosion and wind accumulation of dusts could be shown to increase the variability on the D4-scale. This became most obvious in observations of the large phytogenic mounds developed below shrubs on the Gellap and Nabaos study sites. In the 1-5 centimetre topsoil layer, significantly increased amounts of coarse silt, finest fine sand and middle sand were detected, particle size classes that are known to be transportable by wind (Herrmann, 1996). Further, this process applies to BSC-sites, where the sticky components of algean filaments trap and bind dusts of airborne materials, which could be demonstrated in terms of increased values of silt and several total element contents (compare Paragraph "Establishment of BSC").

6.3 Processes on the Mesoscale (D3 = m^2 - 1000 m^2)

Interactions between ecosystem features and soil properties on the D3-scale are far less numerous than on the micro-scale and are basically related to two processes:

1. water and material translocation
2. biological activity

An example for 1) is the differentiation of D3-units into run-off and run-on zones, of which the generation of rock fringes with their usually humus- and nutrient-enriched soils and and their additional supply with run-off water from adjacent bare rocks results in higher biomass production. This could be demonstrated for small scale study sites in the mountain top area in Soebatsfontein. The same process generally applies for outcrop areas in Gellap and Nabaos although the much harsher climatic conditions make the run-on less effective since these additional water supplies obviously appear much less frequently so that an establishment of plants is not facilitated as clearly as in Soebatsfontein. Instead, rivier structures as D3-units which are receiving more regular and higher amounts of water than other D3-units, show a denser vegetation of adapted shrubs, especially *Catophractes alexandrii* along their edges or in form of vegetated, slightly elevated patches witin these structures, referred to as rivier islands in Chapter 5.4.2. Another example in this context is the differentiation of slopes in Soebatsfontein into the stronger sloped heuweltjies and the more stable matrix units. Fig. 4.14 demonstrates this for the parameter Ca_t along a mesotopographical gradient from the heuweltjie top to the matrix on a transect of approximately 25 m. The relation between Ca_t-content and relative topographical height across this transect initially decreases exponentially from the upper heuweltjie centre to the lower heuweltjie margin. Between the heuweltjie foot (Matrix 1) and the adjacent planar inter-heuweltjie area (Matrix 2), however, the contents of Ca_t are similar.

Processes summed up under point 2) find application in Soebatsfontein in terms of the distinct differentiation of the slopes into matrix and heuweltjie-units (compare Chapter 4.4.2.3). But apart from these features restricted to a belt of approx. 50 km along the west coast of South Africa, other examples occur on other parts of the BIOTA transect. Those are for example the so-called fairy rings that were introduced in the literature review (Chapter 4.4.2.3), and - much more commonly found - the mound structures of the termite species *Macrotermes michaelseni* which would be regarded as D3-structures in the particular ecosystems.

6.4 Large Scale Processes as Determinants of Small Scale Patterns

It was observed that the structuring of landscapes into small scale features and the linked processes are expressed in very distinct ways in the two case-studies. This applies on the one hand to the occurrence and abundance of structures and on the other hand to the degree to which variability is developed. This phenomenon is triggered by large scale processes impacting on the biomes in different ways.

Three factors have to be discussed in this context. The most dominant is probably ***climate***: the climatic conditions of Namaqualand are characterised by highly predictable winter rainfalls with low intensity that, together with additional water supply in terms of sea fogs and dews, favour a denser vegetation. Potential erosion processes on the landscape scale of the Soebatsfontein study site are therefore counteracted in a double sense: by the low erosivity of winter rains on the one hand, and the stabilising effect by high coverage of plant species on the other. By contrast, the predominant rain regime in the Nama-Karoo is summer rainfall, and although the annual amount of precipitation is widely comparable in both biomes and even a bit higher in Gellap/ Nabaos (compare Fig. 4.2 and Fig. 5.2), the low predictability and the thunderstorm-like character of rain events poses a challenge to the establishment of plants which is expressed by much scarcer vegetation.

A second factor is ***geology***. Here again, both ecosystems are to a certain degree comparable, since both are structured geomorphologically into mountains and slightly sloped plains, though these are more inclined in Soebatsfontein; also, both systems are comparable in geological diversity, since one rock type occurs on either site: granites/ granitic gneisses in Soebatsfontein, and shists in Gellap and Nabaos. Yet, the substrates derived from these bedrocks are so different in their properties: soils derived from granites in Soebatsfontein consist of loamy sands. The weathering of these rocks is a rather long-term process and the degree of material translocations is comparatively low. Shists of the Nama-Karoo in contrast prove highly unstable to weathering (compare Chapter 5.3). In interaction with the harsh climate (erosivity of rains, destructive force of high radiation), the geology leads to a landscape-wide homogenisation of soils. This probably accounts for the fact, that small scale structures such as BSC and widely also MSC are missing as well as larger landscape-differentiating structures of biogenic origin such as heuweltjie or *Macrotermes*-mounds.

Factor three impacting on small scale processes is ***landuse***. The effect of this factor could be studied by comparing the D1-sites Gellap (commercial management, low grazing intensity, fenced camps) and Nabaos (communal landuse, high grazing intensities, open access grazing). Apart from observations in previous studies (Petersen, 2008; Wolkenhauer, 2003) that reported of stronger degradation and the lack of grass species on the Nabaos side of the fenceline, findings of this work detected significantly lower nutrients on Nabaos (expressed particularly through the parameters EC and NO_{3we}), a suggested stronger adaption of plants by increased development of fertility islands and an increased amount of D4-structures on the Gellap side (occurrence of grass- and MSC encrusted patches).

6.5 Implications for Landuse Options, Climate Change, Biodiversity and Vulnerability

It could be shown that numerous processes on the small scale, especially the micro-scale (D4), are critical for controlling the redistribution and efficient storage of resources such as water and nutrients, the input of certain elements into the system and the rejuvenation of soil and therefore maintenance of soil fertility. Conclusively, the degree of small scale differentiation of landscapes determines the usability of arid and semi-arid ecosystems as rangelands.

The inventory of drylands in terms of small-scale patches varies; this could be clearly shown by the two case studies in the Succulent Karoo and the Nama Karoo. The degree of small-scale variability is widely determined by large scale preconditions such as climate and geology and as such a natural determination; however, it is further impacted by anthropogenic use where over-utilisation leads to degradation, lower degree of small scale structuring and hence a higher vulnerability of the ecosystem.

Ecosystems with higher structural heterogeneity have to be regarded principally as more stable with regard to vulnerability which includes considerations regarding the maintenance and protection of the inherent biodiversity. This is underlined by a comparison of own findings with the studies of Petersen (2008): the Succulent Karoo as the system with a clearly higher structural heterogenity and corresponding topsoil variability on micro- and meso-scale showing the highest pedo- and biodiversity indices of the BIOTA transect. The comparatively strongly diminished soil variability in the Nama Karoo is in line with the much lower degree of diversity observed for this area.

The question remains, how this stability has to be evaluated with regard to the expected climate change?

The findings of this study indicate a high dependence of the ecosystems on the climate conditions they have adapted to: the majority of rain events occurring in the Succulent Karoo are low erosive winter rains, yet deep erosion gullies incised in the landscape bear witness to the occasionally appearing summer rains and their destructive force. With the expected shift of climate regimes to the South, the summer rains are predicted to become more frequent in this area. While ecosystems like the Nama Karoo may appear less stable due to landscape homogenising effects as described above, they are nonetheless adapted to the harsh conditions and will probably prove to be more resilient when facing the effect of climate change than a system like the Succulent Karoo: while the Nama Karoo will have to cope with decreasing amounts of annual precipitation, the Succulent Karoo will additionally have to cope with a change in rain regime, which is most likely the greater issue.

The effects of climate change will hardly be preventable. Measures taken to ensure sustainability of rangelands, both in terms of biodiversity and in their role as rangelands providing food for an increasing population, have to aim at the maintenance and restoration of small scale patterns, and an appropriate landuse management. This thesis may serve as a reference combining previous and new findings regarding the processes on a small scale, thus providing a crucial background information for the development of action plans.

7 Summary

A part of the ecosystem, soils control the composition and abundance of plants and animals and vice versa. Thus biodiversity and pedodiversity are directly linked and also reflect geologic, topographic, climatic and anthropogenic influences. In drylands, small scale patchiness of soil properties and vegetation affects the distribution of water and nutrients and therefore ecosystem functions. However, despite this obvious significance, processes linking pattern and scale are not yet completely understood in these environments. Therefore, this work aims at investigating the variability of topsoil properties, their scale-dependent patterns, their drivers and underlying processes with the focus on the micro- (dm^2 - 1 m^2) and the mesoscale (1 m^2 - 1000 m^2). The work was conducted within the scope of the BIOTA Southern Africa project and ties in with the work of Petersen (2008), who analysed soils on a habitat and landscape scale on the same sites.

Field work was conducted on or in direct vicinity to three standardised BIOTA observatories of which the "Soebatsfontein" observatory was located in the Succulent Karoo of South Africa and "Gellap" and "Nabaos" in the Namibian Nama Karoo. The study sites were comparable in terms of geologic and geomorphologic diversity and the annual amount of precipitation; yet they differed in rain regime (Succulent Karoo: winter rain, Nama Karoo: summer rain), vegetation and landscape dynamics. The two sites in the Nama Karoo were furthermore differentiated by contrasting landuse practices (Nabaos: communal open access farming, Gellap: commercial land management with fenced camps and grazing control). A special feature of Soebatsfontein is the occurrence of fossil termite mounds, so-called "heuweltjies", in the landscape that exhibit a noteworthy structuring effect.

For the assessment of topsoil variability, the landscapes were subdivided into nested scales in a hierarchical system with

- D1: representing the landscape scale and its degradation state (Succulent Karoo, severely and weakly degraded Nama Karoo)
- D2: structuring the landscape into habitat units (e.g. Mountain Top, Slopes)
- D3: subdividing habitats into mesoscale units (e.g. Matrix soils, heuweltjie centres, heuweltjie margins, different deposits of sedimentation)
- D4: representing the microscale patches (e.g. open soil, plant canopy, biological soil crusts).

Seven small scale study sites covering the most abundant D3-units were established in Soebatsfontein, ranging in size between 20 and 150 m^2. High precision surveys were conducted on each of these sites that generated the basic data for the creation of digital elevation models (DEM). These provided information about the areal range of D3 and D4-units, the distribution of perennial plant species and test- and sampling points. The same approach was applied for Gellap and Nabaos. Here, two small scale study areas were established and surveyed on each site, ranging in size between 1,050 and 5,600 m^2.

Samples of the 0-10 cm topsoil were taken separately with regard to three layers 0-1, 1-5 and 5-10 cm on five locations within each D4-unit. With this procedure, a statistical analysis was assured. The samples were analysed in the laboratory according to a set of standardised parameters that comprised pH, EC, C_{org}, N_t, C_{inorg}, total element contents, watersoluble ions, texture (in composite samples) and plant available nutrients (K_{dl}, P_{dl}). Furthermore, field tests were conducted on selected D4-units on all observatories (determination of topsoil water contents after rain events, single ring infiltration rates).

The data set derived from 498 soil samples in Soebatsfontein and 363 soil samples in Gellap and Nabaos was analysed with regard to the detection of patterns on the D3- and D4-scale, the influence of microtopography and the composition of total variability in the data set in terms of differentiation into units of the scales D1 to D4, differentiation into the three topsoil layers and residual variability, the latter representing the unexplained variability occurring within the scale-units. An additional subchapter dealt with the field test measuring of small-scale hydrology effects.

The main results derived for Soebatsfontein comprised the following findings:

- Total variability was most strongly explained by differentiation of the data into D4- and D3-units, whereas the differentiation into D2-units explained only a small percentage of variability.
- On the D3-scale, differentiation of slopes into heuweltjies and matrix had strong influence on topsoil variability in terms of pH, Ca_t, Mn_t, Zn_t, P_t and plant available nutrients. The expected influence of rock fringe units on rocky outcrop areas in terms of additional nutrient supply was only partly confirmed.
- On the D4-scale, comparisons of biological encrusted (BSC) and non-crusted open soil resulted in higher pH-values, lower C/N-ratios, higher silt contents within the first centimetre and corresponding increased values of particular total element contents (e.g. Mn_t) on BSC-sites. Expected increased values of N_t, C_{org} and nutrients as described in literature were not found.
- Plant canopy sites showed the fertility island-effect: topsoil below plant crowns relative to adjacent open soil was enriched in organic matter, had increased pH-values and higher contents of coarse fractions when comparing the texture. Partly, the soil was also enriched in nutrients.
- Smallscale-topography showed effects on the mesoscale and in some examples explained the variability between D4-units. Correlations between microtopography and selected soil properties within D4-units were not found and could therefore not be used to explain additional percentages of variability below the D4 and Layer-hierarchical level.

The main results derived for Gellap and Nabaos can be summarised as follows:

- D3-units were far less determinant with regard to variability compared to Soebatsfontein due to a strong homogenising effect of landscape dynamics
- D4-patchiness was far less pronounced compared to Soebatsfontein: apart from one crusted and one grassy patch, differentiation on D4-scale was limited to the alteration of open soil and much less abundant shrub patches.
- The comparison of the D4-units open soil and shrub canopy resulted in strong differentiation in terms of increased N_t-, C_{org}, C/N- and EC-values as well as increased infiltration rates below shrubs.
- In terms of microtopography, the size of phytogenic mounds showed strong positive correlations with the parameters pH, EC, K_{dl} and S_t. Between phytogenic mounds and the parameters C_{org}, N_t and C/N-ratios lower r-values were obtained.
- Total variability was not affected by D2 in terms of pH_{H2O} and $EC_{2.5}$, but was more strongly determined by D2 with regard to those parameters that indicated parent material.
- Differences in the two grazing systems were found with regard to higher pH-values in Nabaos which were attributed to geologic effects; lower nutrient contents in Nabaos indicated by lower $NO_3{}^-$-, C_{org}-, N_t- and EC-values; and stronger pronounciation of shrub - open soil differentiation which was referred to either a stronger need of plants for facilitation, or the stronger destruction of C_{org} in open soil patches due to the degradation-induced lack of grasses and other structuring elements.
- Hydrology experiments could exemplify the infiltration-controlled interaction of run-off and run-on on the small scale and the corresponding patchiness of soil water contents after a rain-event.

From the findings on topsoil patchiness in the two case studies, processes on the D4-scale were deduced that are regarded as potential drivers of differentiation in dryland ecosystems in general. The main processes were combined to the process complexes small scale distribution of water, distribution of water-soluble ions, humus and nutrient accumulation and organic matter decomposition, establishment of BSC, bioturbation and trampling, wind erosion and wind accumulation.

On the next hierarchical level, D3, which was also a focus of this work, differentiations were mainly driven by water- and material translocations and by biological activity.

The Succulent Karoo and the Nama Karoo were found to vary strongly in terms of small-scale patterning despite the above-mentioned comparable preconditions. The causes for this phenomenon were linked to large scale impacts such as climate, geology and landuse.

In the conclusion, the implications for further research and future challenges for the management of drylands are outlined.

8 Zusammenfassung

Böden steuern als Bestandteile des Ökosystems das Vorkommen und die Zusammensetzung von Tier- und Pflanzenarten. Umgekehrt beeinflussen auch die Arten maßgeblich die Ausprägung von Bodeneigenschaften. Somit sind Biodiversität und Pedodiversität eng miteinander verbunden und spiegeln außerdem geologische, topographische, klimatische und anthropogene Einflüsse wider. Die kleinskalige Variabilität von Bodeneigenschaften übt insbesondere in Trockengebieten maßgeblich Einfluss auf die Verteilung von Wasser und Nährstoffen aus und beeinflußt damit auch die Funktionalität der Ökosysteme. Die den Mustern zugrundeliegenden Prozesse und ihre skalenbasierte Wirksamkeit werden trotz ihrer augenscheinlichen Bedeutung noch immer nicht verstanden. Aus diesem Grund beleuchtet diese Arbeit die Variabilität von Oberböden in Trockengebieten, deren skalenabhängige Muster und deren zugrundeliegende Faktoren und Prozesse mit Schwerpunkt auf der Mikro- (dm^2 bis 1 m^2) und der Mesoskala (1 m^2 bis etwa 1000 m^2). Die Dissertation wurde im Rahmen des vom BMBF geförderten Verbundprojektes BIOTA Südafrika erarbeitet und knüpft inhaltlich an die Dissertation von Petersen (2008) an, der die Pedodiversität derselben Flächen auf Habitat- und Landschaftsskala untersucht hat.

Die Geländearbeiten zur vorliegenden Arbeit wurden auf oder in unmittelbarer Nähe zu drei standardisierten BIOTA-Observatorien durchgeführt, wobei sich das Observatorium „Soebatsfontein“ in der südafrikanischen Sukkulenten Karoo und die Observatorien „Gellap“ und „Nabaos“ in der namibianischen Nama Karoo befinden. Diese Untersuchungsflächen weisen eine vergleichbare geologische und geomorphologische Diversität und eine ähnliche Menge an Gesamtjahresniederschlag auf. Andererseits unterschieden sie sich stark durch das Wirken unterschiedlicher Regenregime (Sukkulenten Karoo: Winterregengebiet, Nama Karoo: Sommerregengebiet) sowie durch die vorherrschenden Vegetationsformen und den Grad der Landschaftsdynamik. Darüberhinaus unterschieden sich die beiden Flächen in der Nama Karoo durch unterschiedliche Landnutzungsformen (Nabaos: kommunales Weideland mit unbeschränkter Nutzung, Gellap: kommerziell geführter Betrieb mit kontrollierter Rotationsbeweidung). Eine Besonderheit des Standorts Soebatsfontein war das Auftreten zahlreicher fossiler Termitenhügel, der sog. „Heuweltjies“, die einen deutlich strukturierenden Einfluss auf die Landschaft ausüben.

Für die Untersuchung der Oberbodenvariabilität wurde ein Untersuchungsansatz gewählt, der die Landschaft wie folgt in ineinandergeschachtelte Einheiten gemäß eines hierarchischen Systems untergliedert:

- D1: repräsentiert die Landschaftseinheit und ihren Degradationszustand (Sukkulenten Karoo, schwach und stark degradierte Nama Karoo)
- D2: strukturiert die Landschaft in Habitat-Einheiten (z. B. Bergkuppe, Hänge)
- D3: untergliedert die Habitat-Einheiten in sog. Meso-Einheiten (z. B. Matrixböden, Heuweltjie-Center, Heuweltjie-Ränder, verschiedene Ablagerungen von Sedimenten unterschiedlichen Alters)
- D4: repräsentiert Einheiten der Mikro-Skala (z. B. offene Bodenflächen, Kronenbereiche, biologische Bodenkrusten)

In Soebatsfontein wurden sieben Teilflächen ausgewiesen, die die flächenmäßig am stärksten ausgeprägten D3-Einheiten umfassten. Diese waren zwischen 20 und 150 m^2 groß. Die Flächen wurden in großer Dichte kleinräumig mit einem Tachymeter vermessen, anschließend wurden aus den Koordinaten 3D-Geländemodelle (DEM) generiert. Diese lieferten Informationen über die flächenhafte Abgrenzung der D3- und D4-Einheiten, die Verteilung von perennierenden Pflanzenarten und über Proben- und Teststandorte. Der gleiche Ansatz wurde auf den Untersuchungsgebieten Gellap und Nabaos durchgeführt. Die hier etablierten Teilflächen waren größer und wiesen eine Fläche zwischen 1050 und 5600 m^2 auf.

Oberbodenproben wurden in drei Schichten 0-1, 1-5 und 5-10 cm an fünf Stellen innerhalb einer beprobten D4-Einheit entnommen. Durch diese Vorgehensweise wurde eine statistische Auswertung der Daten gewährleistet. Die Proben wurden im Labor gemäß einer Anzahl an Standardparametern analysiert. Dazu gehörten die Parameter pH, Leitfähigkeit, C_{org}, N_t, C_{inorg}, Elementgesamtgehalte, wasserlösliche Ionen, Bodenart (aus Mischproben) und pflanzenverfügbare Nährstoffe (K_{dl} und P_{dl}). Darüberhinaus wurden auf ausgewählten D4-Einheiten im Gelände Feldtests durchgeführt. Diese bestanden aus der Bestimmung des Wassergehaltes im Oberboden nach einem Regenereignis und Einring-Infiltrationstests.

Der untersuchte Gesamtdatensatz umfasst 498 Bodenproben aus Soebatsfontein und 363 Bodenproben aus Gellap und Nabaos. Dieser wurde hinsichtlich der Musterbildungen auf D3- und D4-Skala, des Einflusses der Mikrotopographie und der Zusammensetzung der Gesamtvariabilität untersucht. Für letzteres wurde berechnet, wie stark die Differenzierungen in D1- bis D4-Gruppen und in verschiedene Bodenschichten die Gesamtvariabilität im Datensatz beeinflussen. Ein zusätzliches Teilkapitel befasst sich mit kleinräumigen Effekten der untersuchten hydrologischen Eigenschaften.

Für das Untersuchungsgebiet Soebatsfontein ergaben sich folgende Hauptergebnisse:

- Die Gesamtvariabilität wurde am stärksten durch die Gliederung der Landschaft in D4- und D3-Einheiten erklärt. Der Differenzierung in D2-Einheiten konnte dagegen nur ein geringer Anteil an der Gesamtvariabilität zugewiesen werden.
- Innerhalb der D3-Skala hatte die Differenzierung der Hänge in Heuweltjies und Matrixflächen eine starke Variabilität der Oberbödeneigenschaften hinsichtlich der Parameter pH, Ca_t, Mn_t, Zn_t, P_t und pflanzenverfügbarer Nährstoffe zur Folge.
- Auf D4-Skala resultierten Vergleiche von offenen Oberböden mit und ohne biologischer Bodenkruste (BSC) in höheren pH-Werten, engeren C/N-Verhältnissen und höheren Schluff-Gehalten des ersten Zentimeters sowie den damit verbundenen erhöhten Gehalten bestimmter Elementgesamtgehalte (z.B. Mn_t) auf BSC-Standorten. Die in der Literatur beschriebenen erhöhten N_t-, C_{org}- und Nährstoffgehalte an BSC-Standorten trafen auf die vorliegenden Daten hingegen nicht zu.
- Proben aus Kronenbereichen von Zwergsträuchern wiesen einen Effekt auf, der in der englischsprachigen Literatur als „Fertile-Island-Effect“ beschrieben wird: Oberböden unter Strauchkronen zeigten - relativ zu angrenzenden offenen Bodenflächen - Anreicherungen von organischer Substanz, sie wiesen erhöhte pH-Werte auf und zeichneten sich außerdem durch höhere Gehalte der Grobfraktionen in den Körnungsdaten aus. Zum Teil konnten auch Nährstoffanreicherungen in Böden der Kronenbereiche nachgewiesen werden.
- Die kleinräumige Topographie zeigte Effekte auf der Mesoskala. Außerdem erklärte sie in einigen Beispielen die Variabilität zwischen D4-Einheiten. Es konnten aber keine Korrelationen zwischen kleinräumiger Topographie und ausgewählten Bodenparametern innerhalb von D4-Einheiten nachgewiesen werden, somit konnte die Mikrotopographie nicht als weiterer erklärender Faktor unterhalb der hierarchischen Einheiten „D4“ und „Bodenschichten“ in die Gesamtvariabilitätsanalyse integriert werden.

Für Gellap und Nabaos lassen sich folgende Hauptergebnisse feststellen:

- D3-Einheiten waren im Vergleich zu Soebatsfontein weit weniger variabilitätsbestimmend, was auf eine höhere Dynamik der Landschaftsprozesse zurückgeführt wurde.
- Die Differenzierung der Landschaft auf D4-Skala war weit weniger ausgeprägt als in Soebatsfontein. Neben einer Krusten- und einer grasbestandenen Kleinstfläche war die Landschaftsdifferenzierung auf dieser Skala auf den Wechsel von offenen Bodenflächen und weit kleinflächigeren Kronenbereichen von Sträuchern reduziert.

- Der Vergleich der D4-Einheiten „offene Bodenflächen“ und „Kronenraum von Sträuchern“ ergab eine Differenzierung der Oberböden durch erhöhte N_t-, C_{org}-, C/N- und Leitfähigkeitswerte sowie erhöhte Infiltrationsraten unter Sträuchern.

- Mikrotopographische Analysen führten zu der Erkenntnis, dass ein positivkorrelierender Zusammenhang zwischen dem Grad der Ausprägung von Sedimentakkumulationen unter Sträuchern (sog. „phytogenic mounds“, Abk. „PGM“) und bestimmten Parametern wie pH, Leitfähigkeit, K_{dl} und S_t besteht. Zwischen den PGM und den Parametern C_{org}, N_t und C/N-Verhältnis waren ebenfalls Korrelationen nachweisbar, allerdings waren diese weit schwächer ausgeprägt.

- Die Gesamtvariabilität der pH- und Leitfähigkeitswerte wurde kaum durch die Untergliederung in D2-Einheiten beeinflußt. Allerdings wurde ein starker Einfluss auf die Gesamtvariabilität durch D2-Einheiten in solchen Parametern ausgeübt, die das Ausgangsgestein charakterisieren.

- Zwischen den beiden Flächen mit unterschiedlichen Beweidungssytemen konnten Unterschiede in den Bodeneigenschaften festgestellt werden. Diese zeigten sich durch geringere Nährstoff-Gehalte in Nabaos, die durch geringe NO_3^--, C_{org}-, N_t- und Leitfähigkeitswerte indiziert wurden, und durch eine stärkere Ausprägung der Differenzierung in Kronenraum und offene Bodenflächen, die dadurch erklärt wurde, dass
    (a) Pflanzen sich entweder an die harscheren Lebensbedingungen durch eine Aufakkumulation von Nährstoffen anpassen oder dass
    (b) der höhere Anteil an offenen Bodenflächen durch degradationsbedingten Rückgang der Gräser zu einer verstärkten strahlungsinduzierten C_{org}-Zerstörung im Boden führten.

- Anhand der hydrologischen Untersuchungen konnte exemplarisch die infiltrationsgesteuerte kleinräumige Wechselwirkung von Ablauf- und Zuschusszonen nach einem Regenereignis sowie die daraus resultierende inhomogene Verteilung des Wassergehaltes im Oberboden dargestellt werden.

Anhand von zwei Fallbeispielen wurden aus den Ergebnissen der kleinräumigen Untersuchungen der Oberbodeneigenschaften Prozesse auf D4-Skala abgeleitet, die als potentielle Verursacher der kleinräumigen Landschaftsdifferenzierung in Trockengebieten betrachtet werden. Diese Prozesse wurden zu folgenden Prozesskomplexen zusammengefaßt: kleinräumige Verteilung von Wasser, Verteilung wasserlöslicher Ionen, Humus- und Nährstoffakkumulation sowie Zersetzung organischer Substanz, Etablierung biologischer Bodenkrusten, Bioturbation und Viehvertritt, Winderosion und Windakkumulation.

Als landschaftsdifferenzierende Prozesse der nächsten hierarchischen Einheit D3, die ebenfalls in dieser Arbeit eingehender betrachtet wurde, wurden vor allem Wasser- und Materialtranslokationen sowie die biologische Aktivität definiert.

Zwischen der Sukkulenten und der Nama Karoo wurden trotz der oben genannten vergleichbaren Ausgangsbedingungen starke Unterschiede in der Ausprägung kleinräumiger Bodenmuster festgestellt. Diese Tatsache wurde auf den Einfluss höher skaliger Prozesse wie Klima, Geologie und Landnutzung zurückgeführt.

Abschließend wurden Schlussfolgerungen zu weiteren Forschungsaktivitäten und zu zukünftig hinsichtlich des Klimawandels anzupassenden Bewirtschaftungsformen der Trockengebiete gezogen.

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A Appendix for Soebatsfontein

A.1 Reference Profiles

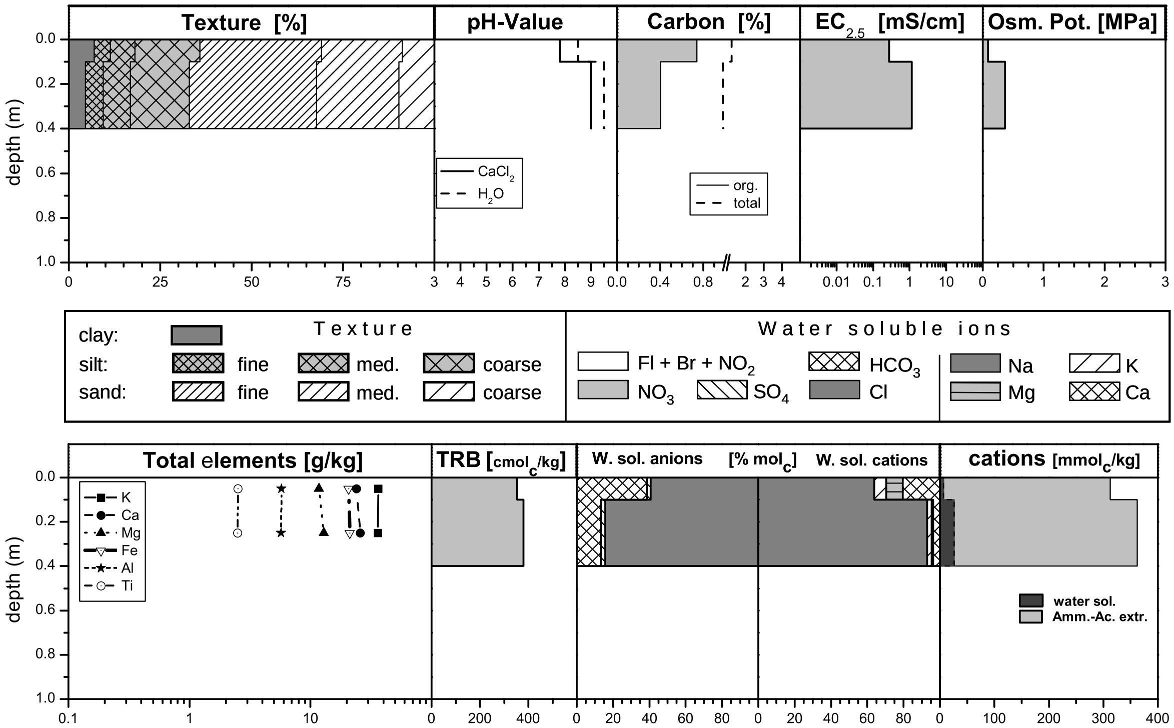

Fig. A.1: Reference profile for Heuweltjie Centre-unit on Accumulation Zone (AC-HC): BIOTA profile P213: Calcic Solonchak. [9]

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[9] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

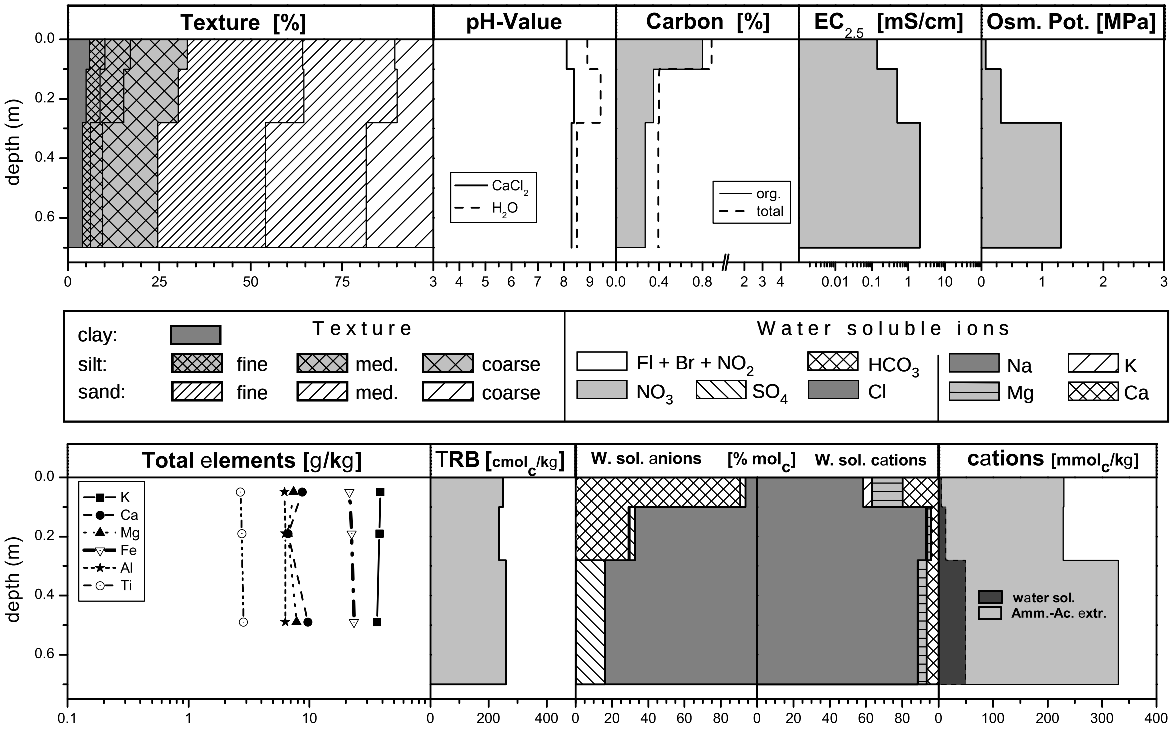

Fig. A.2: Reference profile for Heuweltjie Matrix-unit on Accumulation Zone (AC-HM): BIOTA profile P214: Duric Hypersalic Solonchak. [10]

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[10] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

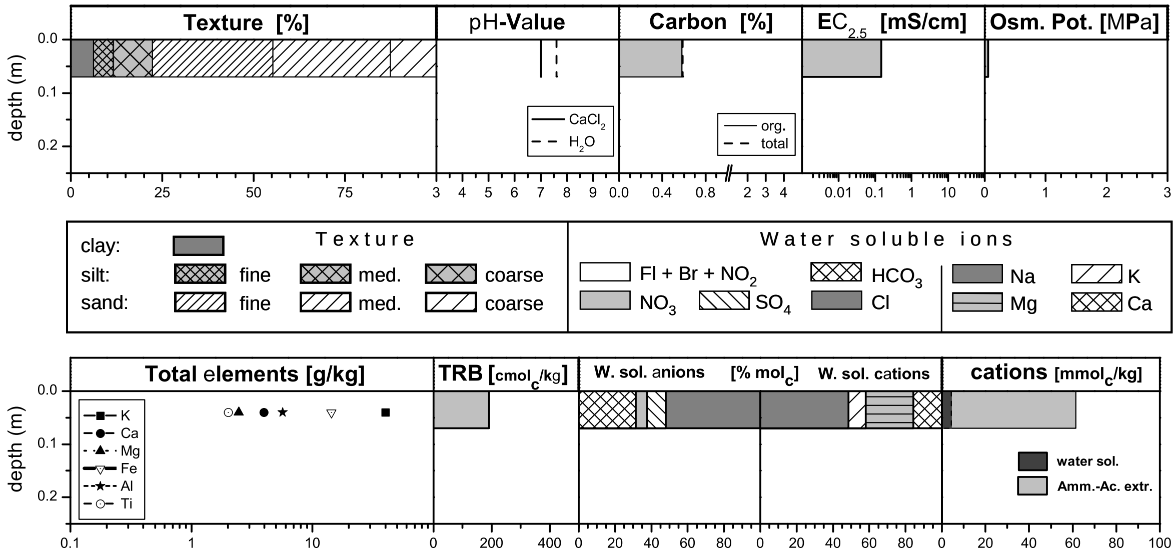

Fig. A.3: Reference profile for Matrix-unit on Accumulation Zone (AC-MA): BIOTA profile P215: Epipetric Durisol (Arenic). [11]

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[11] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

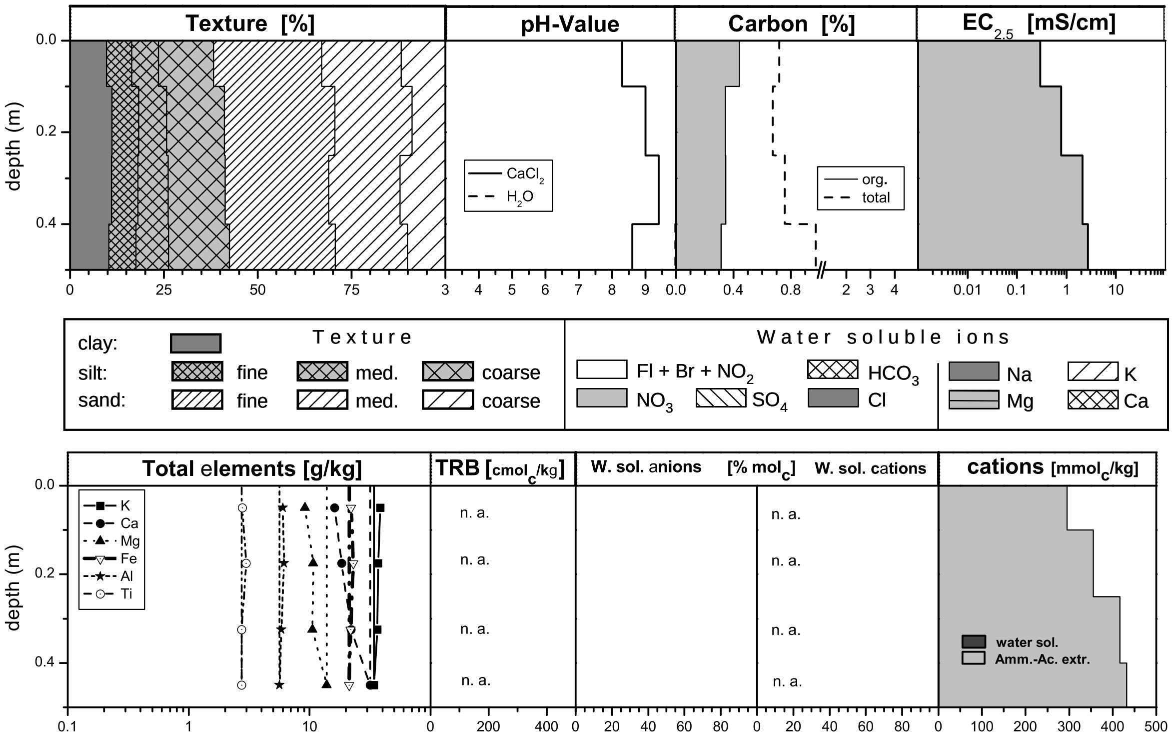

Fig. A.4: Reference profile for Heuweltjie Centre-unit on Western Slope (WS-HM): BIOTA profile P851: Hypersalic Solonchak.

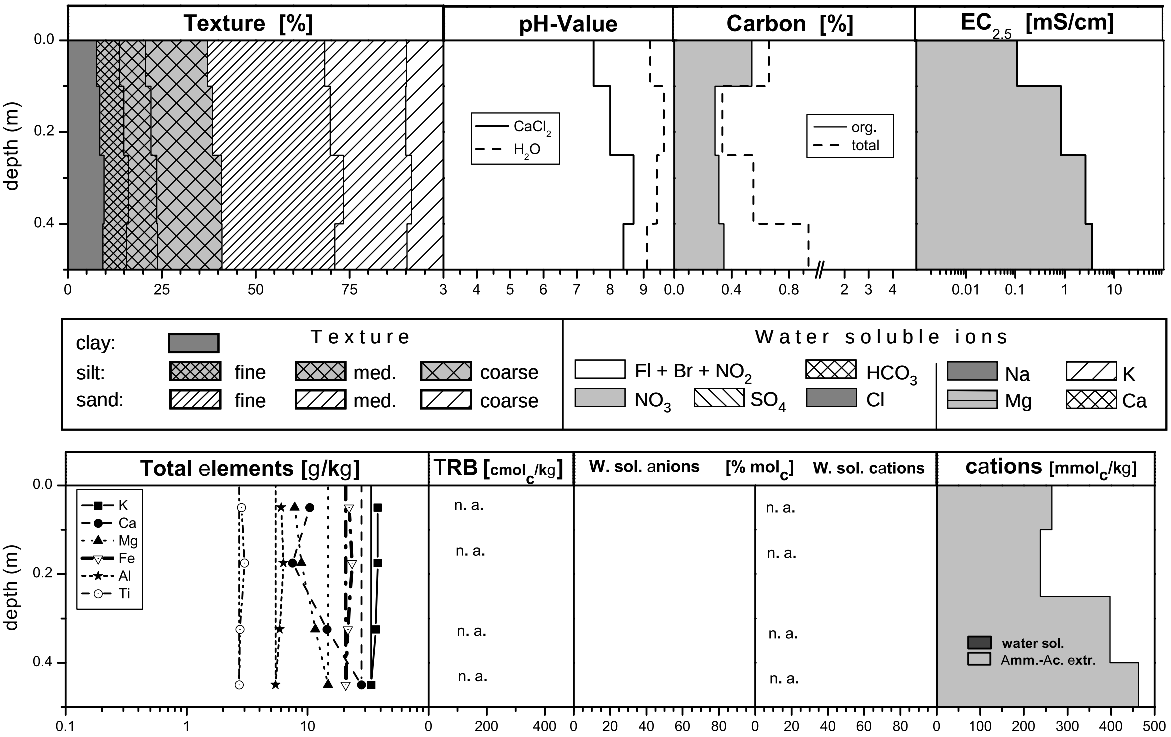

Fig. A.5: Reference profile for Heuweltjie Margin-unit on Western Slope (WS-HM): BIOTA profile P850: Hypersalic Solonchak.

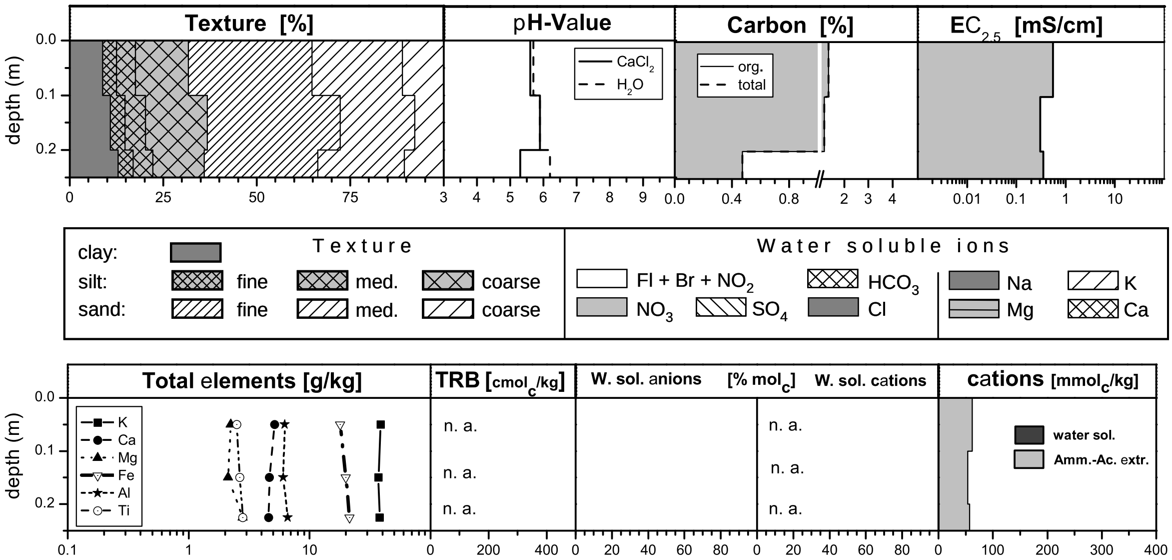

Fig. A.6: Reference profile for Matrix-unit on Western Slope (WS-MA): BIOTA profile P829: Epipetric Durisol.

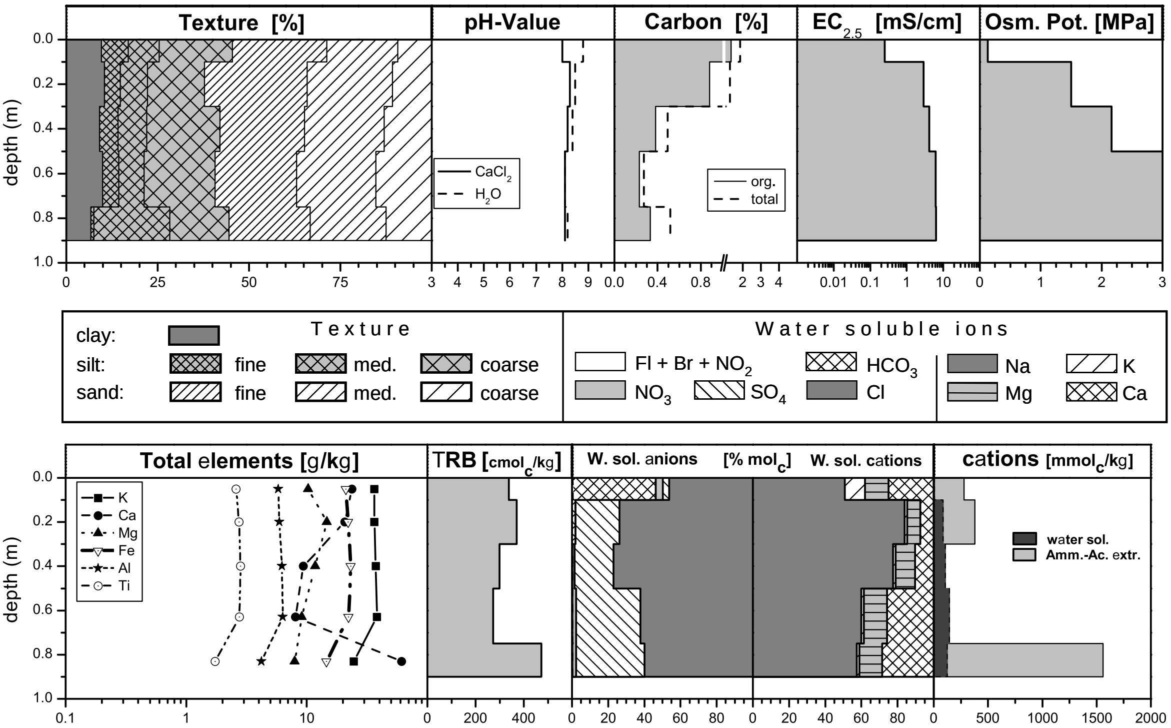

Fig. A.7: Reference profile for Heuweltjie Center-unit on Lower Eastern Slope (ES-HC): BIOTA profile P533: Duric Gypsic Hypersalic Solonchak. [12]

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[12] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

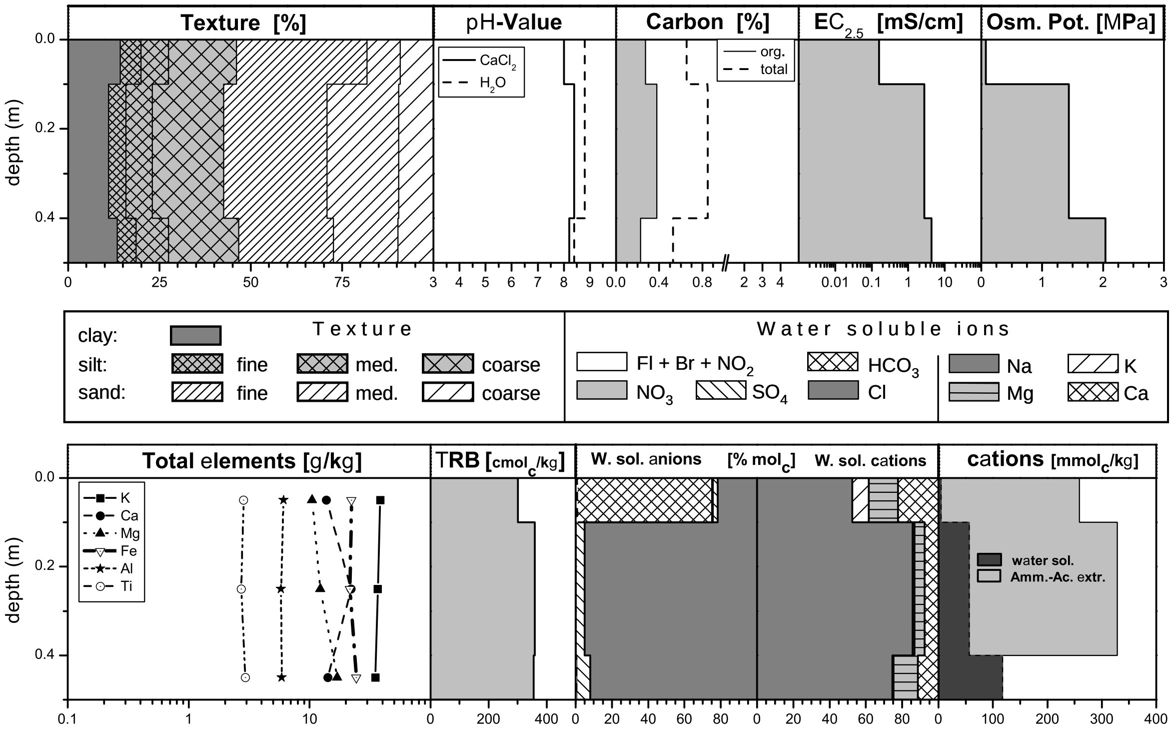

Fig. A.8: Reference profile for Heuweltjie Matrix-unit on Lower Eastern Slope (ES-HM): BIOTA profile P534: Hypocalcic Duric Hypersalic Solonchak (Aridic). [13]

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[13] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

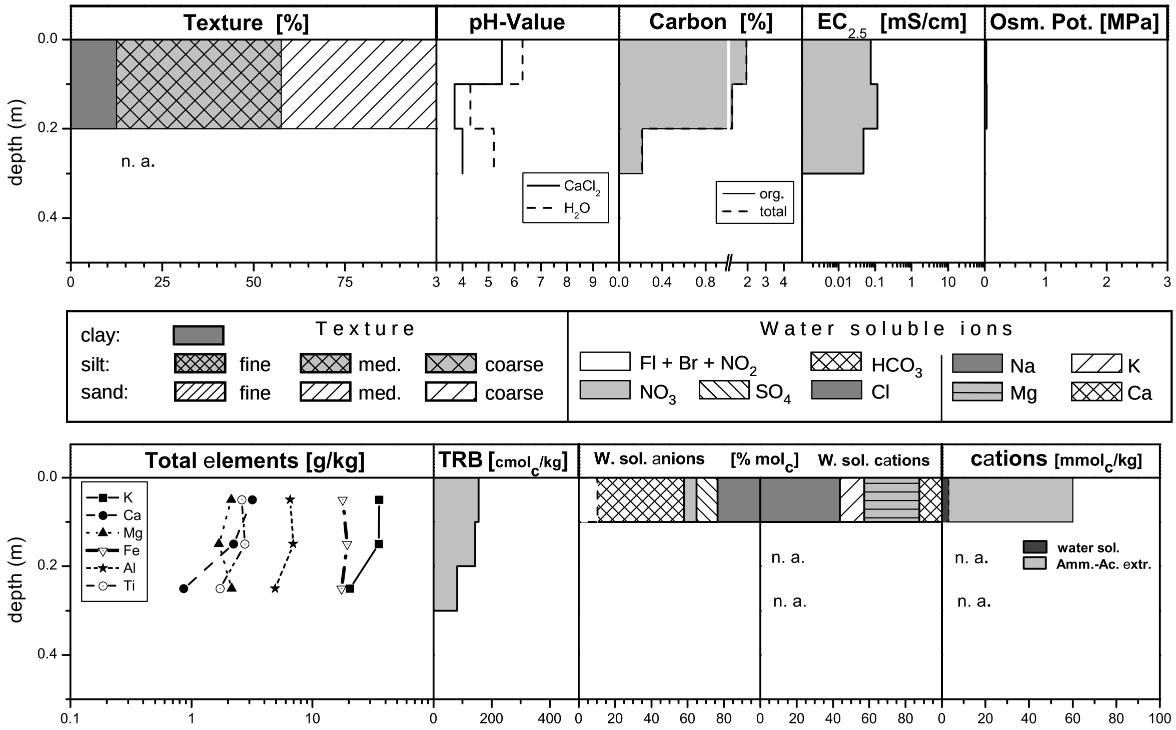

Fig. A.9: Reference profile for Matrix-unit within quartz field on Lower Eastern Slope (ES-MA2): BIOTA profile P220: Hyperskeletic Leptosol (Humic, Dystric). [14]

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[14] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

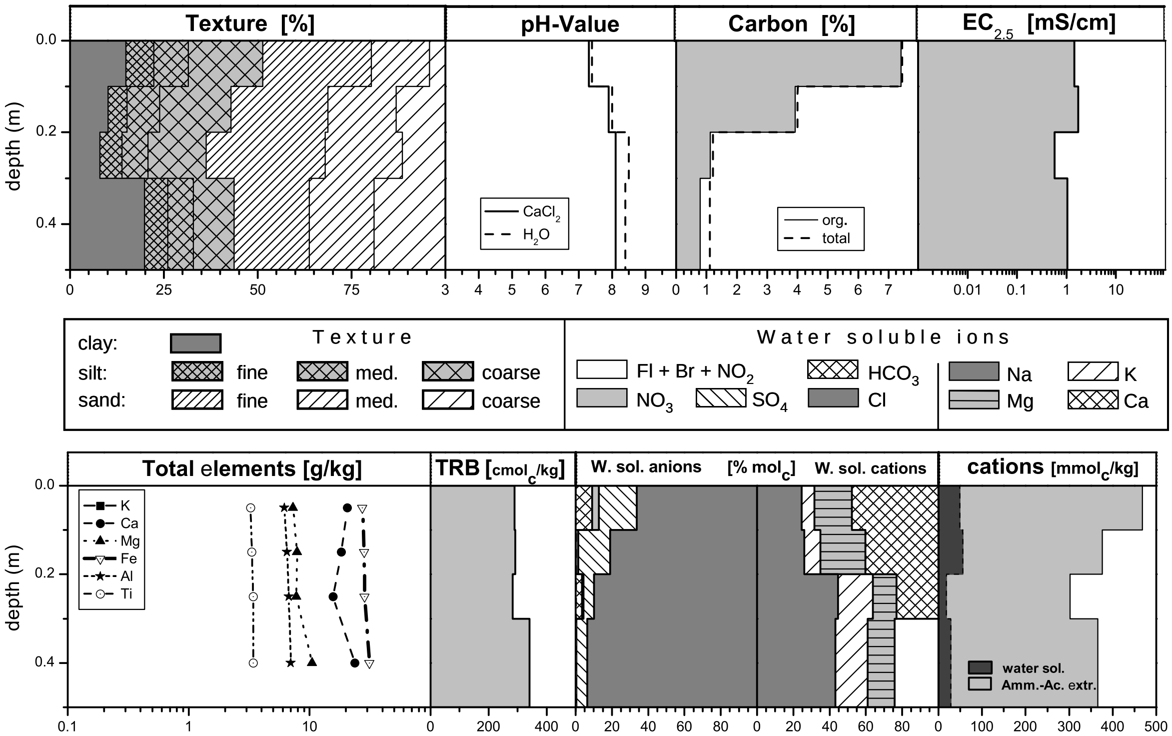

Fig. A.10: Reference profile for Rock-Fringe-unit on Mountain Top (MT-RF1): BIOTA-profile P209: Haplic Cambisol (Calcaric, Hypereutric, Episkeletic).[15]

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[15] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

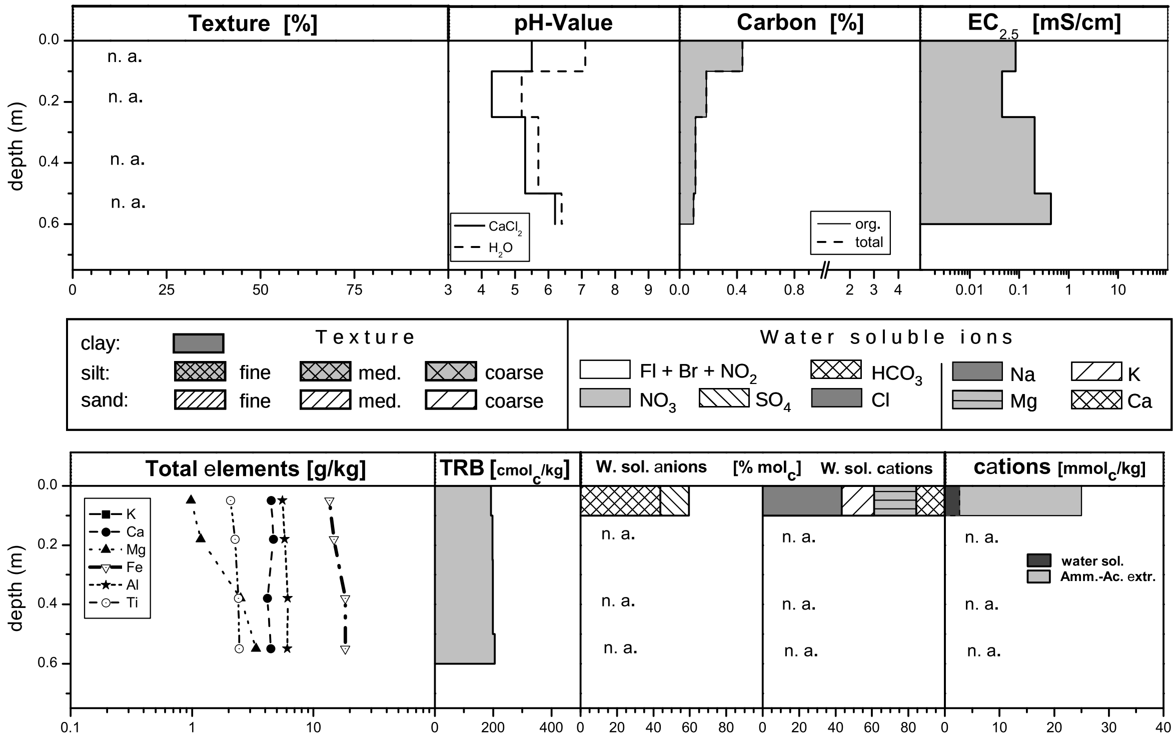

Fig. A.11: Reference profile for Matrix-unit on Mid-Eastern Slope (MS-MA2): BIOTA-profile P210: Endopetric Durisol (Arenic, Chromic).[16]

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[16] Graphics and classification according to WRB (2006) kindly provided by Andreas Petersen. Data available on www.biota-africa.org.

A.2 Comparison of Heuweltjie- and Matrix-units on D3-Scale

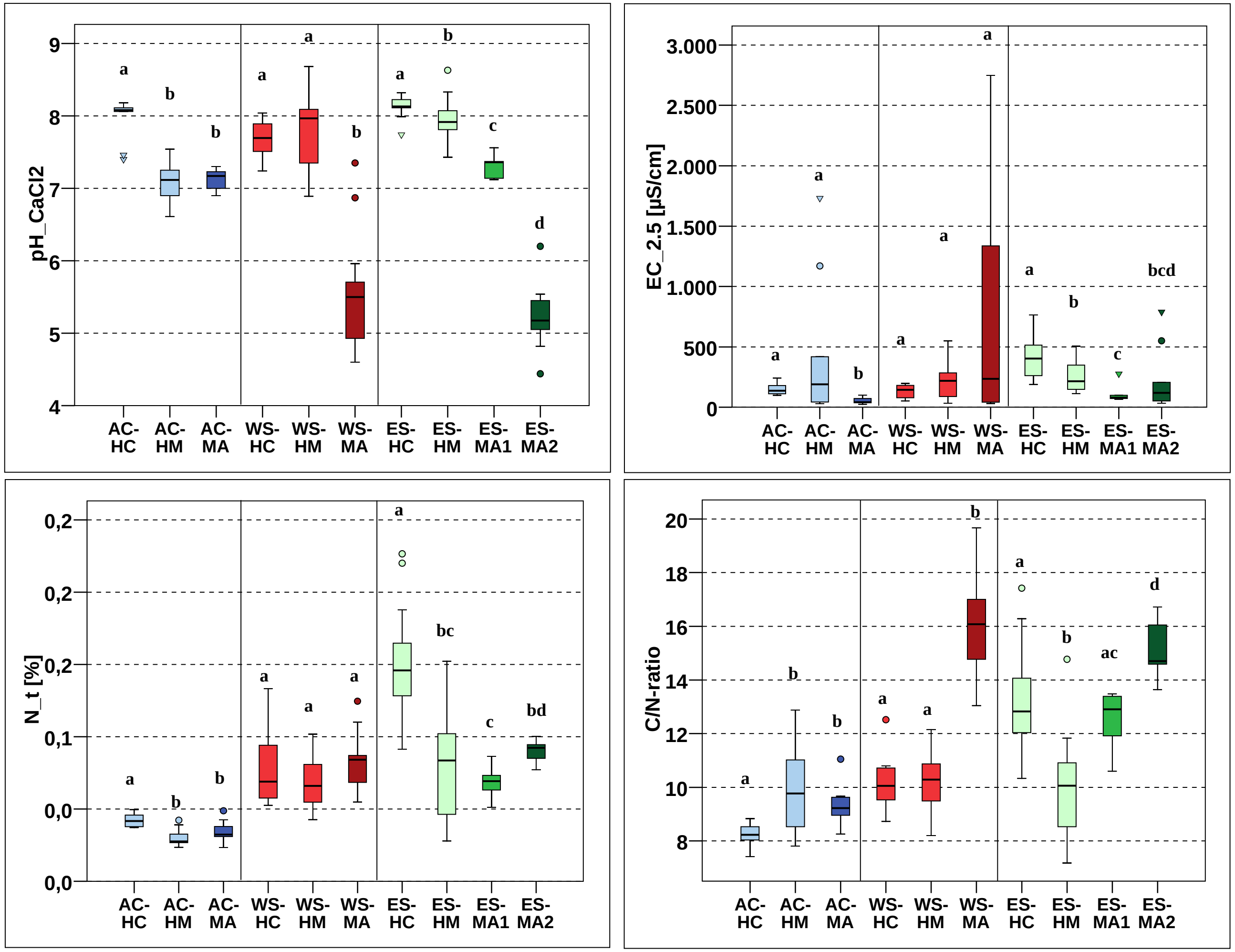


Fig. A.12: Comparison of Heuweltjie- and Matrix-units on D3-scale (I): Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Accumulation Zone (AC) in blue colours, Western Slope (WS) in red colours, Lower Eastern Slope (ES) in green colours; darker colours designate Matrix-units. Different letters indicate significant differences with p = 0.05.

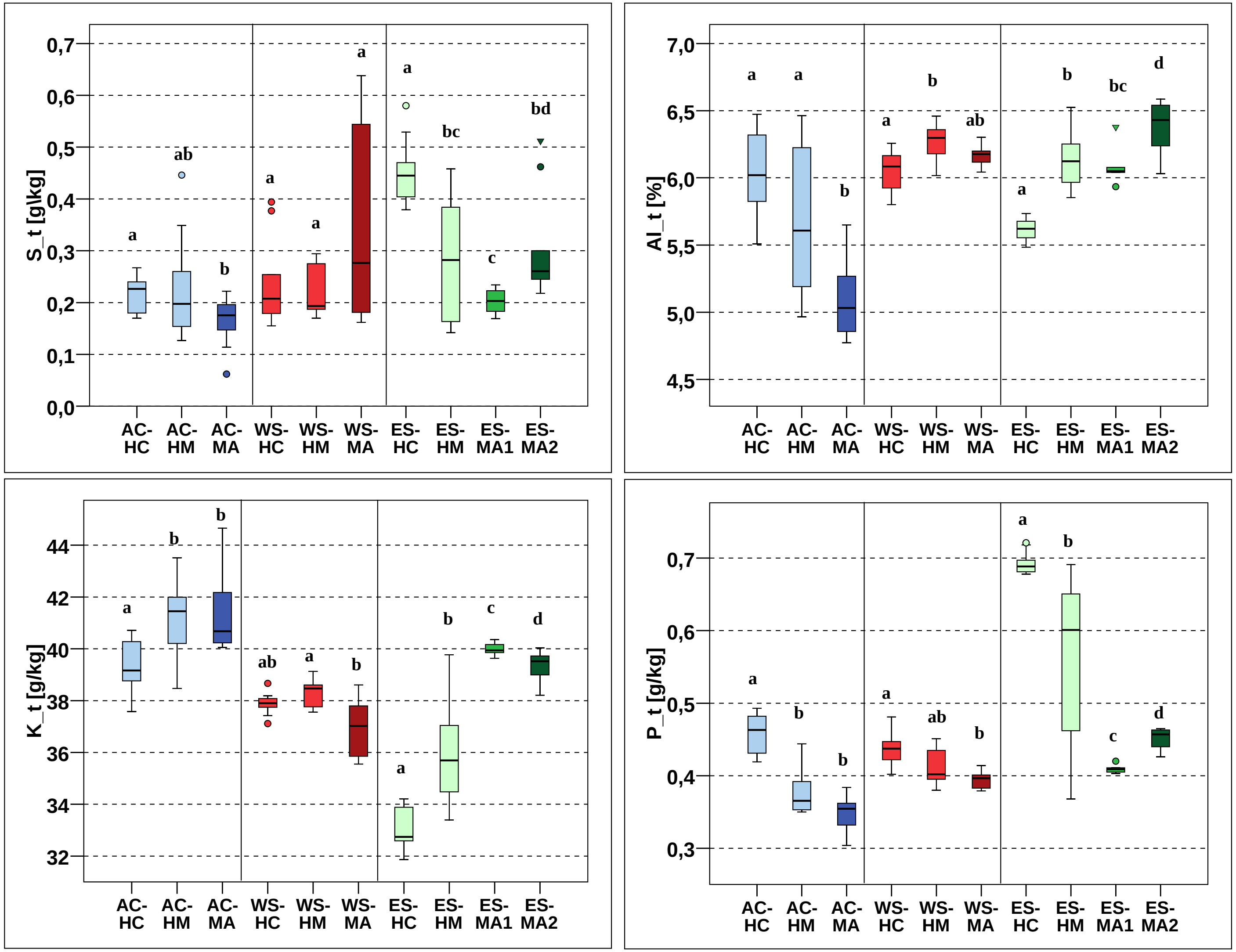


Fig. A.13: Comparison of Heuweltjie- and Matrix-units on D3-scale (II): Boxplots are based on weighted means over 0-10 cm of each miniprofile. Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Accumulation Zone (AC) in blue colours, Western Slope (WS) in red colours, Lower Eastern Slope (ES) in green colours; darker colours designate Matrix-units. Different letters indicate significant differences with p = 0.05.

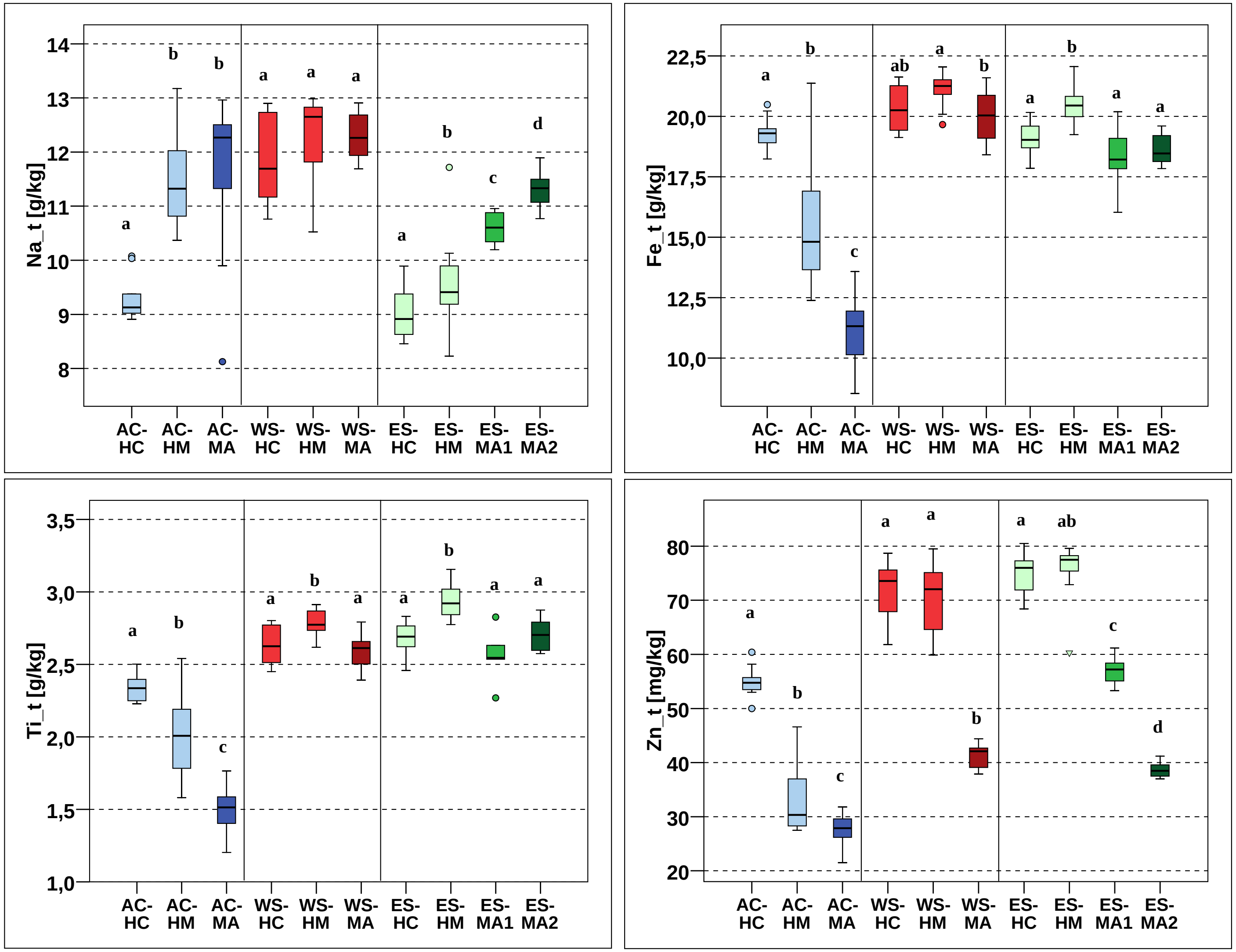


Fig. A.14: Comparison of Heuweltjie- and Matrix-units on D3-scale (III): Boxplots are based on weighted means over 0-10 cm of each miniprofile. Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Accumulation Zone (AC) in blue colours, Western Slope (WS) in red colours, Lower Eastern Slope (ES) in green colours; darker colours designate Matrix-units. Different letters indicate significant differences with p = 0.05.

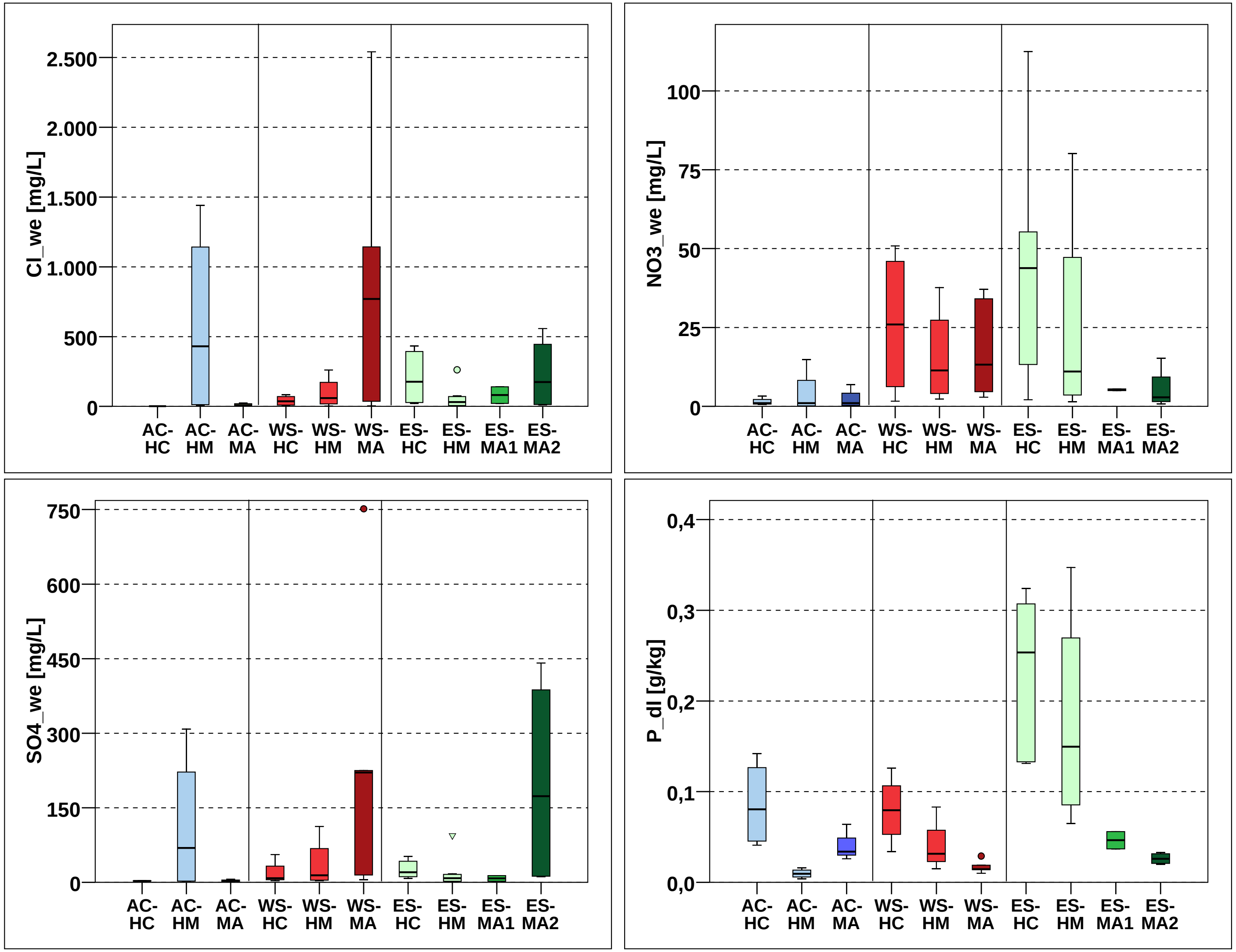


Fig. A.15: Comparison of Heuweltjie- and Matrix-units on D3-scale (IVI): Boxplots are based on weighted means over 0-10 cm of each miniprofile. Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Accumulation Zone (AC) in blue colours, Western Slope (WS) in red colours, Lower Eastern Slope (ES) in green colours; darker colours designate Matrix-units. Significance tests were omitted due to low samples numbers of partly < 5.

	AC-HC		AC-HM		AC-MA		WS-HC		WS-HM		WS-MA	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH$_{H2O}$	10	9.2 $^{(a)}$ ± 0.4	10	8.1 $^{(b)}$ ± 0.7	10	8.7 $^{(c)}$ ± 0.3	10	9.0 $^{(a)}$ ± 0.4	10	9.1 $^{(a)}$ ± 0.7	15	5.8 $^{(b)}$ ± 0.6
pH$_{CaCl2}$	10	8.0 $^{(a)}$ ± 0.3	10	7.1 $^{(b)}$ ± 0.3	10	7.1 $^{(b)}$ ± 0.1	10	7.7 $^{(a)}$ ± 0.2	10	7.8 $^{(a)}$ ± 0.5	15	5.5 $^{(b)}$ ± 0.8
EC$_{2.5}$ [µS/cm]	10	149 $^{(a)}$ ± 44	10	427 $^{(a)}$ ± 570	10	51 $^{(b)}$ ± 24	10	132 $^{(a)}$ ± 56	10	227 $^{(a)}$ ± 168	15	687 $^{(a)}$ ± 838
EC$_5$ [µS/cm]	10	111 $^{(a)}$ ± 33	10	253 $^{(a)}$ ± 340	10	35 $^{(b)}$ ± 16	10	120 $^{(a)}$ ± 53	10	184 $^{(a)}$ ± 137	15	426 $^{(a)}$ ± 507
C$_{org}$ [%]	10	0.35 $^{(a)}$ ± 0.05	9	0.30 $^{(a)}$ ± 0.07	10	0.32 $^{(a)}$ ± 0.09	10	0.82 $^{(a)}$ ± 0.38	10	0.72 $^{(a)}$ ± 0.27	15	1.31 $^{(b)}$ ± 0.39
N$_t$ [%]	10	0.042 $^{(a)}$ ± 0.004	9	0.031 $^{(b)}$ ± 0.006	10	0.034 $^{(b)}$ ± 0.007	10	0.079 $^{(a)}$ ± 0.028	10	0.070 $^{(a)}$ ± 0.020	15	0.082 $^{(a)}$ ± 0.018
C/N-ratio	10	8.2 $^{(a)}$ ± 0.4	9	10.0 $^{(b)}$ ± 1.6	10	9.3 $^{(b)}$ ± 0.7	10	10.2 $^{(a)}$ ± 1.1	10	10.2 $^{(a)}$ ± 1.1	15	16.0 $^{(b)}$ ± 1.9
K$_{dl}$ [g/kg]	4	0.33 ± 0.06	4	0.30 ± 0.16	3	0.17 ± 0.02	4	0.51 ± 0.09	4	0.59 ± 0.16	6	0.23 ± 0.02
P$_{dl}$ [g/kg]	4	0.086 ± 0.049	4	0.010 ± 0.005	3	0.041 ± 0.02	4	0.080 ± 0.038	4	0.040 ± 0.030	6	0.017 ± 0.007
S$_t$ [g/kg]	10	0.22 $^{(a)}$ ± 0.03	10	0.23 $^{(ab)}$ ± 0.10	10	0.17 $^{(b)}$ ± 0.05	10	0.23 $^{(a)}$ ± 0.09	10	0.22 $^{(a)}$ ± 0.05	10	0.35 $^{(a)}$ ± 0.18
Al$_t$ [%]	10	6.02 $^{(a)}$ ± 0.31	10	5.70 $^{(a)}$ ± 0.55	10	5.11 $^{(b)}$ ± 0.30	10	6.06 $^{(a)}$ ± 0.15	10	6.27 $^{(b)}$ ± 0.13	10	6.17 $^{(ab)}$ ± 0.08
Na$_t$ [g/kg]	10	9.30 $^{(a)}$ ± 0.42	10	11.44 $^{(b)}$ ± 0.87	10	11.59 $^{(b)}$ ± 1.51	10	11.83 $^{(a)}$ ± 0.77	10	12.29 $^{(a)}$ ± 0.79	10	12.30 $^{(a)}$ ± 0.40
K$_t$ [g/kg]	10	39.3 $^{(a)}$ ± 1.1	10	41.2 $^{(b)}$ ± 1.5	10	41.3 $^{(b)}$ ± 1.5	10	37.9 $^{(ab)}$ ± 0.4	10	38.3 $^{(a)}$ ± 0.5	10	36.9 $^{(b)}$ ± 1.1
Ca$_t$ [g/kg]	10	13.02 $^{(a)}$ ± 3.72	10	3.64 $^{(b)}$ ± 0.32	10	3.50 $^{(b)}$ ± 0.33	10	9.77 $^{(a)}$ ± 4.18	10	7.79 $^{(a)}$ ± 3.08	10	5.01 $^{(b)}$ ± 0.18
P$_t$ [g/kg]	10	0.46 $^{(a)}$ ± 0.03	10	0.38 $^{(b)}$ ± 0.03	10	0.35 $^{(b)}$ ± 0.03	10	0.44 $^{(a)}$ ± 0.02	10	0.41 $^{(ab)}$ ± 0.03	10	0.40 $^{(b)}$ ± 0.01
Ti$_t$ [g/kg]	10	2.34 $^{(a)}$ ± 0.10	10	2.01 $^{(b)}$ ± 0.29	10	1.51 $^{(c)}$ ± 0.16	10	2.64 $^{(a)}$ ± 0.13	10	2.79 $^{(b)}$ ± 0.09	10	2.60 $^{(a)}$ ± 0.13
Fe$_t$ [g/kg]	10	19.3 $^{(a)}$ ± 0.7	10	15.5 $^{(b)}$ ± 2.7	10	11.2 $^{(c)}$ ± 1.4	10	20.4 $^{(ab)}$ ± 1.0	10	21.1 $^{(a)}$ ± 0.7	10	20.0 $^{(b)}$ ± 1.1
Mn$_t$ [mg/kg]	10	0.66 $^{(a)}$ ± 0.07	10	0.20 $^{(b)}$ ± 0.10	10	0.17 $^{(b)}$ ± 0.03	10	0.92 $^{(a)}$ ± 0.14	10	0.91 $^{(a)}$ ± 0.12	10	0.18 $^{(b)}$ ± 0.03
Zn$_t$ [mg/kg]	10	55.0 $^{(a)}$ ± 2.8	10	32.9 $^{(b)}$ ± 6.2	10	27.4 $^{(c)}$ ± 3.2	10	71.7 $^{(a)}$ ± 5.5	10	70.4 $^{(a)}$ ± 6.8	10	41.2 $^{(b)}$ ± 2.2
Cl$_{we}$ [mg/l]	4	1.7 ± 0.5	4	576.9 ± 696.2	4	10.8 ± 10.6	4	39.9 ± 37.3	4	95 .5 ± 115.6	5	898.7 ± 1038.6
NO$_{3we}$ [mg/l]	4	1.5 ± 1.2	4	4.2 ± 7.1	4	2.3 ± 3.2	4	26.1 ± 23.6	4	15.7 ± 15.9	5	18.4 ± 16.2
SO$_{4we}$ [mg/l]	4	3.1 ± 0.3	4	112.3 ± 144.9	4	3.5 ± 1.9	4	19.1 ± 24.8	4	36.2 ± 51.8	5	243.5 ± 303.3

Tab. A.1: Comparison of Heuweltjie and Matrix-units on three D2-sites. Means and SD were calculated from weighted means over 0-10 cm for each miniprofile. Different letters within each D2-unit indicate significant differences at $p < 0.05$. — continued.

	PH-HC		PH-HM		PH-MA		PH-QF	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH$_{H2O}$	15	9.3 $^{(a)}$ ± 0.3	20	9.6 $^{(b)}$ ± 0.3	5	8.1 $^{(c)}$ ± 0.3	10	6.1 $^{(d)}$ ± 0.6
pH$_{CaCl2}$	15	8.1 $^{(a)}$ ± 0.1	20	8.0 $^{(b)}$ ± 0.2	5	7.3 $^{(c)}$ ± 0.2	10	5.2 $^{(d)}$ ± 0.5
EC$_{2.5}$ [µS/cm]	15	411 $^{(a)}$ ± 169	20	250 $^{(b)}$ ± 119	5	119 $^{(c)}$ ± 89	10	213 $^{(bcd)}$ ± 253
EC$_5$ [µS/cm]	15	295 $^{(a)}$ ± 110	20	206 $^{(b)}$ ± 91	5	85 $^{(c)}$ ± 52	10	141 $^{(cd)}$ ± 178
C$_{org}$ [%]	15	2.06 $^{(a)}$ ± 0.83	20	0.93 $^{(b)}$ ± 0.59	5	0.89 $^{(ac)}$ ± 0.26	10	1.35 $^{(d)}$ ± 0.16
N$_t$ [%]	15	0.149 $^{(a)}$ ± 0.039	20	0.083 $^{(bc)}$ ± 0.038	5	0.069 $^{(c)}$ ± 0.013	10	0.090 $^{(bd)}$ ± 0.008
C/N-ratio	15	13.2 $^{(a)}$ ± 1.9	20	10.1 $^{(b)}$ ± 1.7	5	12.5 $^{(ac)}$ ± 1.2	10	15.1 $^{(d)}$ ± 1.0
K$_{dl}$ [g/kg]	6	0.73 ± 0.23	8	0.60 ± 0.37	2	0.56 ± 0.14	4	0.19 ± 0.02
P$_{dl}$ [g/kg]	6	0.234 ± 0.087	8	0.178 ± 0.110	2	0.047 ± 0.013	4	0.026 ± 0.006
S$_t$ [g/kg]	10	0.45 $^{(a)}$ ± 0.06	15	0.29 $^{(bc)}$ ± 0.11	5	0.20 $^{(c)}$ ± 0.03	10	0.30 $^{(bd)}$ ± 0.10
Al$_t$ [%]	10	5.62 $^{(a)}$ ± 0.09	15	6.14 $^{(b)}$ ± 0.22	5	6.10 $^{(bc)}$ ± 0.17	10	6.37 $^{(d)}$ ± 0.19
Na$_t$ [g/kg]	10	9.01 $^{(a)}$ ± 0.48	15	9.57 $^{(b)}$ ± 0.79	5	10.60 $^{(c)}$ ± 0.33	10	11.32 $^{(d)}$ ± 0.33
K$_t$ [g/kg]	10	33.0 $^{(a)}$ ± 0.8	15	35.8 $^{(b)}$ ± 1.7	5	40.0 $^{(c)}$ ± 0.3	10	39.4 $^{(d)}$ ± 0.5
Ca$_t$ [g/kg]	10	30.37 $^{(a)}$ ± 2.39	15	14.41 $^{(b)}$ ± 6.71	5	4.69 $^{(c)}$ ± 0.27	10	3.90 $^{(d)}$ ± 0.16
P$_t$ [g/kg]	10	0.69 $^{(a)}$ ± 0.02	15	0.56 $^{(b)}$ ± 0.12	5	0.41 $^{(c)}$ ± 0.01	10	0.45 $^{(d)}$ ± 0.01
Ti$_t$ [g/kg]	10	2.69 $^{(a)}$ ± 0.12	15	2.94 $^{(b)}$ ± 0.11	5	2.56 $^{(a)}$ ± 0.20	10	2.71 $^{(a)}$ ± 0.11
Fe$_t$ [g/kg]	10	19.1 $^{(a)}$ ± 0.8	15	20.5 $^{(b)}$ ± 0.8	5	18.3 $^{(a)}$ ± 1.5	10	18.6 $^{(a)}$ ± 0.6
Mn$_t$ [mg/kg]	10	1.21 $^{(a)}$ ± 0.04	15	1.10 $^{(b)}$ ± 0.16	5	0.64 $^{(c)}$ ± 0.03	10	0.22 $^{(d)}$ ± 0.03
Zn$_t$ [mg/kg]	10	75.2 $^{(a)}$ ± 3.8	15	75.9 $^{(ab)}$ ± 4.7	5	57.0 $^{(c)}$ ± 3.0	10	38.7 $^{(d)}$ ± 1.3
Cl$_{we}$ [mg/l]	5	210.3 ± 195.5	8	60.3 ± 86.3	2	81.2 ± 84.5	4	229.4 ± 265. 3
NO$_{3we}$ [mg/l]	5	45.4 ± 43.3	8	25.7 ± 29.6	2	5.3 ± 0.4	4	5.4 ± 6.6
SO$_{4we}$ [mg/l]	5	27.1 ± 19.5	8	18.7 ± 31.1	2	8.1 ± 8.0	4	199.9 ± 220.9

Tab. A.2: — continued.

A.3 Comparison of Rock Fringe and Matrix-units on D3-Scale

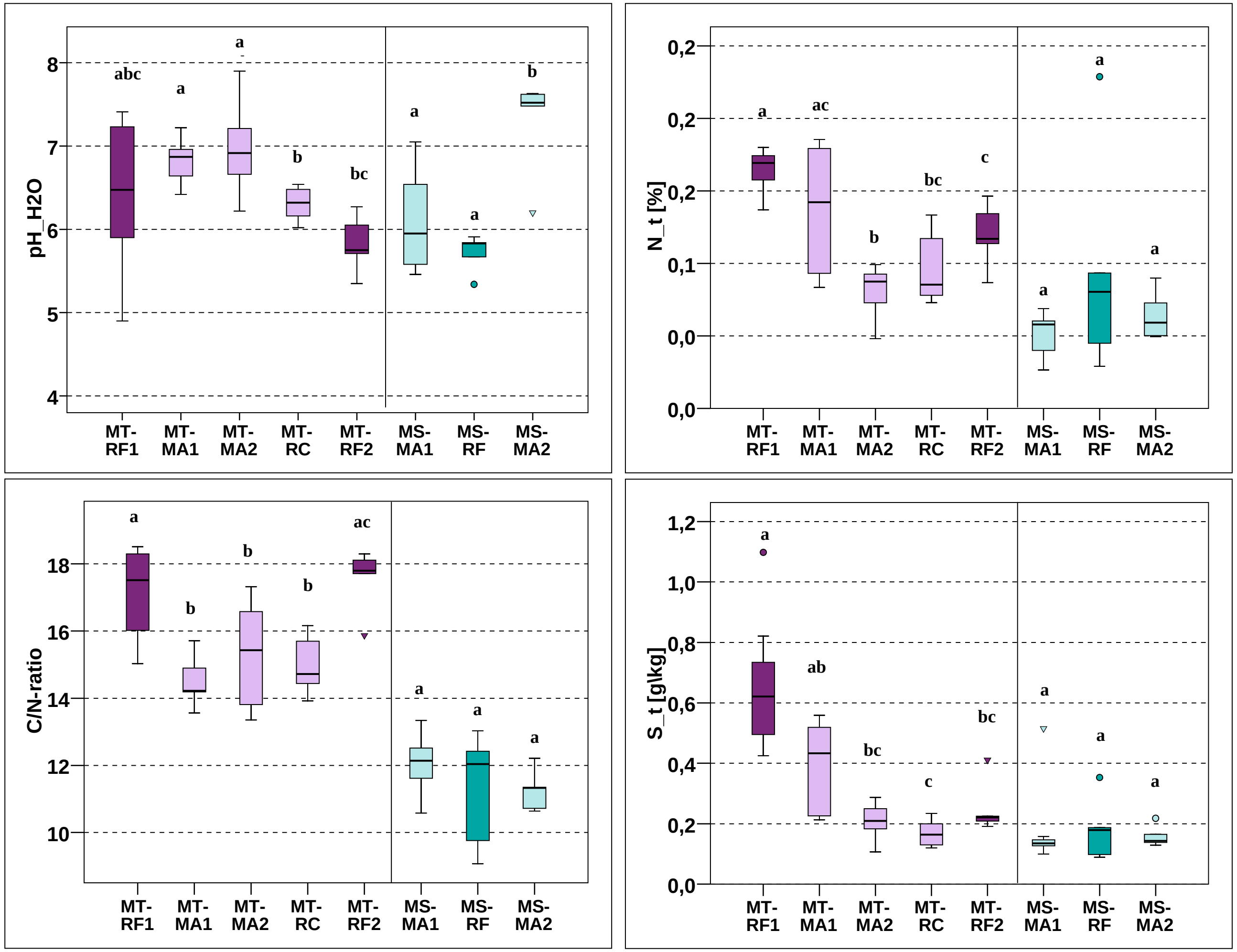


Fig. A.16: Comparison of Rock Fringe and Matrix-units on D3-scale (I): Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Mountain Top (MT) in violett colours, Mid-Eastern Slope (MS) in turquoise colours; darker colours designate Rock Fringe-units. Different letters indicate significant differences with $p = 0.05$.

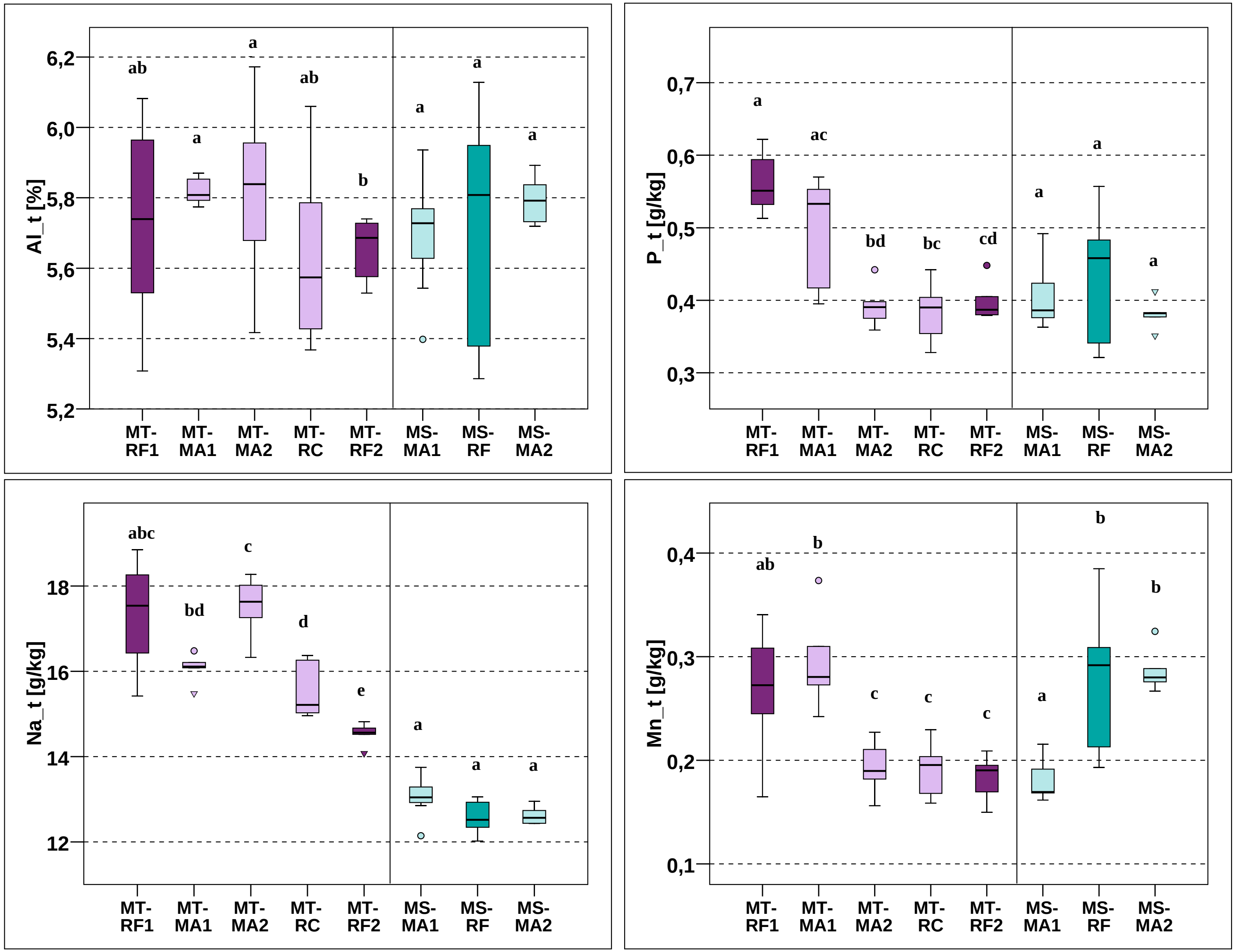


Fig. A.17: Comparison of Rock Fringe and Matrix-units on D3-scale (II): Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Mountain Top (MT) in violett colours, Mid-Eastern Slope (MS) in turquoise colours; darker colours designate Rock Fringe-units. Different letters indicate significant differences with $p = 0.05$.

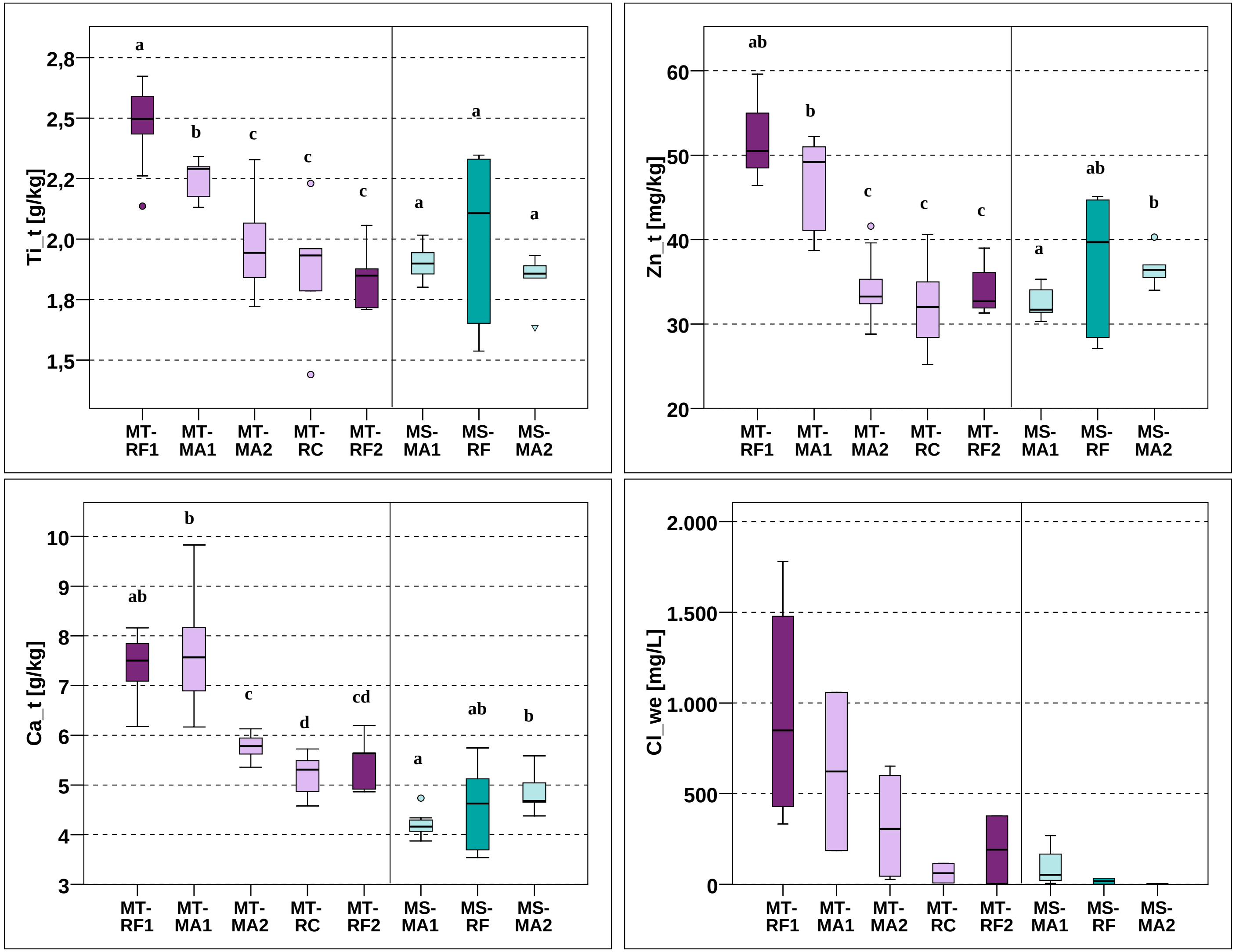


Fig. A.18: Comparison of Rock Fringe and Matrix-units on D3-scale (III): Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Mountain Top (MT) in violett colours, Mid-Eastern Slope (MS) in turquoise colours; darker colours designate Rock Fringe-units. Different letters indicate significant differences with $p = 0.05$. Significance tests of watersoluble anions were omitted due to low samples numbers of partly < 5.

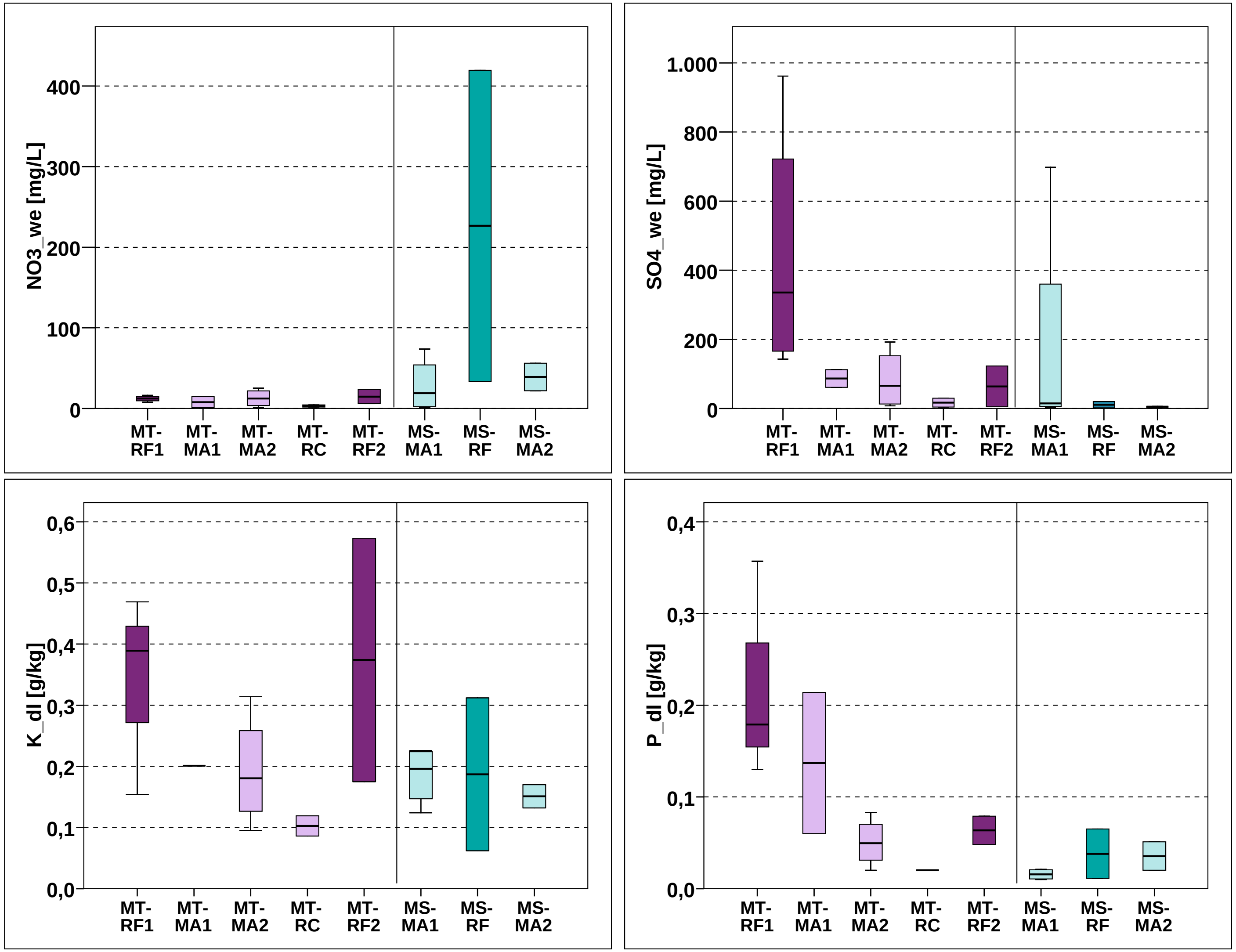


Fig. A.19: Comparison of Rock Fringe and Matrix-units on D3-scale (IV): Boxplots are based on weighted means over 0-10 cm of each miniprofile. D2 Mountain Top (MT) in violett colours, Mid-Eastern Slope (MS) in turquoise colours; darker colours designate Rock Fringe-units. Significance tests of watersoluble anions were omitted due to low samples numbers of partly < 5.

	MT-RF1		MT-MA1		MT-MA2		MT-RC		MT-RF2		MS-MA1		MS-RF		MS-MA2	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH$_{\mathrm{H2O}}$	10	6.4$^{(abc)}$ ± 0.8	5	6.8$^{(a)}$ ± 0.3	10	7.0$^{(a)}$ ± 0.5	5	6.3$^{(b)}$ ± 0.2	5	5.8$^{(bc)}$ ± 0.4	7	6.1$^{(a)}$ ± 0.6	5	5.7$^{(a)}$ ± 0.2	5	7.3$^{(b)}$ ± 0.6
pH$_{\mathrm{CaCl2}}$	10	5.9$^{(abd)}$ ± 0.9	5	6.6$^{(a)}$ ± 0.4	10	6.0$^{(ad)}$ ± 0.5	5	5.4$^{(bc)}$ ± 0.3	5	4.9$^{(c)}$ ± 0.4	7	5.0$^{(a)}$ ± 0.5	5	4.8$^{(a)}$ ± 0.1	5	6.5$^{(b)}$ ± 0.5
EC$_{2.5}$ [µS/cm]	10	1045$^{(a)}$ ± 474	5	563$^{(b)}$ ± 485	10	291$^{(bc)}$ ± 253	5	87$^{(c)}$ ± 63	5	146$^{(bc)}$ ± 223	7	153$^{(a)}$ ± 239	5	119$^{(a)}$ ± 117	5	67$^{(a)}$ ± 24
EC$_{5}$ [µS/cm]	10	687$^{(a)}$ ± 359	5	363$^{(b)}$ ± 282	10	192$^{(bc)}$ ± 170	5	57$^{(c)}$ ± 36	5	103$^{(bc)}$ ± 151	7	93$^{(a)}$ ± 153	5	65$^{(a)}$ ± 69	5	43$^{(a)}$ ± 13
C$_{\mathrm{org}}$ [%]	10	2.84$^{(a)}$ ± 0.31	5	2.01$^{(bc)}$ ± 0.78	10	1.27$^{(b)}$ ± 0.29	5	1.48$^{(bc)}$ ± 0.49	5	2.15$^{(c)}$ ± 0.41	7	0.62$^{(a)}$ ± 0.21	5	1.14$^{(a)}$ ± 0.98	5	0.73$^{(a)}$ ± 0.21
N$_{t}$ [%]	10	0.166$^{(a)}$ ± 0.013	5	0.137$^{(ac)}$ ± 0.047	10	0.081$^{(b)}$ ± 0.016	5	0.097$^{(bc)}$ ± 0.026	5	0.12$^{(c)}$ ± 0.023	7	0.051$^{(a)}$ ± 0.016	5	0.095$^{(a)}$ ± 0.079	5	0.064$^{(a)}$ ± 0.017
C/N-ratio	10	17.2$^{(a)}$ ± 1.2	5	14.5$^{(b)}$ ± 0.8	10	15.3$^{(b)}$ ± 1.5	5	15.0$^{(b)}$ ± 0.9	5	17.6$^{(ac)}$ ± 1.0	7	12.0$^{(a)}$ ± 0.9	5	11.3$^{(a)}$ ± 1.7	5	11.3$^{(a)}$ ± 0.6
K$_{\mathrm{dl}}$ [g/kg]	3	0.34 ± 0.16	2	0.20 ± <0.01	4	0.19 ± 0.09	2	0.10 ± 0.02	2	0.37 ± 0.28	4	0.19 ± 0.05	2	0.19 ± 0.18	2	0.15 ± 0.03
P$_{\mathrm{dl}}$ [g/kg]	3	0.222 ± 0.119	2	0.137 ± 0.109	4	0.051 ± 0.026	2	0.020 ± <0.001	2	0.064 ± 0.022	4	0.016 ± 0.006	2	0.038 ± 0.038	2	0.036 ± 0.022
S$_{t}$ [g/kg]	10	0.64$^{(a)}$ ± 0.21	5	0.39$^{(ab)}$ ± 0.16	10	0.21$^{(bc)}$ ± 0.05	5	0.17$^{(c)}$ ± 0.05	5	0.25$^{(bc)}$ ± 0.09	7	0.19$^{(a)}$ ± 0.15	5	0.18$^{(a)}$ ± 0.11	5	0.16$^{(a)}$ ± 0.04
Al$_{t}$ [%]	10	5.72$^{(ab)}$ ± 0.28	5	5.82$^{(a)}$ ± 0.04	10	5.82$^{(a)}$ ± 0.22	5	5.64$^{(ab)}$ ± 0.28	5	5.65$^{(b)}$ ± 0.09	7	5.69$^{(a)}$ ± 0.18	5	5.71$^{(a)}$ ± 0.36	5	5.79$^{(a)}$ ± 0.07
Na$_{t}$ [g/kg]	10	17.32$^{(abc)}$ ± 1.18	5	16.07$^{(bd)}$ ± 0.37	10	17.54$^{(c)}$ ± 0.61	5	15.57$^{(d)}$ ± 0.69	5	14.53$^{(e)}$ ± 0.28	7	13.05$^{(a)}$ ± 0.49	5	12.57$^{(a)}$ ± 0.42	5	12.62$^{(a)}$ ± 0.22
K$_{t}$ [g/kg]	10	36.8$^{(a)}$ ± 0.7	5	39.2$^{(b)}$ ± 1.2	10	41.0$^{(c)}$ ± 0.6	5	41.2$^{(bc)}$ ± 1.2	5	40.8$^{(bc)}$ ± 0.9	7	40.5$^{(a)}$ ± 0.5	5	40.2$^{(ab)}$ ± 1.9	5	41.5$^{(b)}$ ± 0.5
Ca$_{t}$ [g/kg]	10	7.39$^{(ab)}$ ± 0.62	5	7.73$^{(b)}$ ± 1.39	10	5.77$^{(c)}$ ± 0.25	5	5.19$^{(d)}$ ± 0.47	5	5.45$^{(cd)}$ ± 0.56	7	4.21$^{(a)}$ ± 0.28	5	4.55$^{(ab)}$ ± 0.94	5	4.87$^{(b)}$ ± 0.47
P$_{t}$ [g/kg]	10	0.56$^{(a)}$ ± 0.04	5	0.50$^{(ac)}$ ± 0.08	10	0.39$^{(bd)}$ ± 0.02	5	0.38$^{(bc)}$ ± 0.04	5	0.40$^{(cd)}$ ± 0.03	7	0.41$^{(a)}$ ± 0.05	5	0.43$^{(a)}$ ± 0.10	5	0.38$^{(a)}$ ± 0.02
Ti$_{t}$ [g/kg]	10	2.47$^{(a)}$ ± 0.17	5	2.25$^{(b)}$ ± 0.09	10	1.96$^{(c)}$ ± 0.18	5	1.87$^{(c)}$ ± 0.29	5	1.84$^{(c)}$ ± 0.14	7	1.90$^{(a)}$ ± 0.08	5	1.99$^{(a)}$ ± 0.38	5	1.83$^{(a)}$ ± 0.11
Fe$_{t}$ [g/kg]	10	18.1$^{(a)}$ ± 1.2	5	15.4$^{(b)}$ ± 0.8	10	13.0$^{(c)}$ ± 1.6	5	13.0$^{(bc)}$ ± 2.4	5	13.2$^{(c)}$ ± 1.3	7	14.0$^{(a)}$ ± 0.8	5	14.8$^{(a)}$ ± 2.5	5	13.6$^{(a)}$ ± 0.8
Mn$_{t}$ [mg/kg]	10	0.27$^{(ab)}$ ± 0.05	5	0.30$^{(b)}$ ± 0.05	10	0.19$^{(c)}$ ± 0.02	5	0.19$^{(c)}$ ± 0.03	5	0.18$^{(c)}$ ± 0.02	7	0.18$^{(a)}$ ± 0.02	5	0.28$^{(b)}$ ± 0.08	5	0.29$^{(b)}$ ± 0.02
Zn$_{t}$ [mg/kg]	10	51.6$^{(ab)}$ ± 4.2	5	46.4$^{(b)}$ ± 6.1	10	34.2$^{(c)}$ ± 3.9	5	32.2$^{(c)}$ ± 6.0	5	34.2$^{(c)}$ ± 3.3	7	32.6$^{(a)}$ ± 1.9	5	37.0$^{(ab)}$ ± 8.7	5	36.6$^{(b)}$ ± 2.3
Cl$_{\mathrm{we}}$ [mg/l]	4	953.0 ± 658.7	2	622.8 ± 616.8	4	322.9 ± 323.4	2	62.2 ± 76.5	2	191.8 ± 263.2	4	94.9 ± 118.7	2	17.7 ± 23.0	2	2.5 ± 1.2
NO$_{\mathrm{3we}}$ [mg/l]	4	12.3 ± 3.7	2	7.8 ± 9.7	4	12.7 ± 11.1	2	3.1 ± 1.8	2	14.7 ± 12.5	4	28.3 ± 34.0	2	226.6 ± 272.8	2	39.1 ± 24.0
SO$_{\mathrm{4we}}$ [mg/l]	4	444.0 ± 376.4	2	86.7 ± 36.2	4	82.9 ± 86.9	2	17.1 ± 18.2	2	63.9 ± 83.4	4	182.8 ± 343.5	2	10.9 ± 12.9	2	5.0 ± 2.1

Tab. A.3: Comparison of Rock Fringe and Matrix-units on two D2-sites. Means and SD were calculated from weighted means over 0-10 cm for each miniprofile. Different letters within each D2-unit indicate significant differences at $p < 0.05$.

A.4 Microtopographical Effects

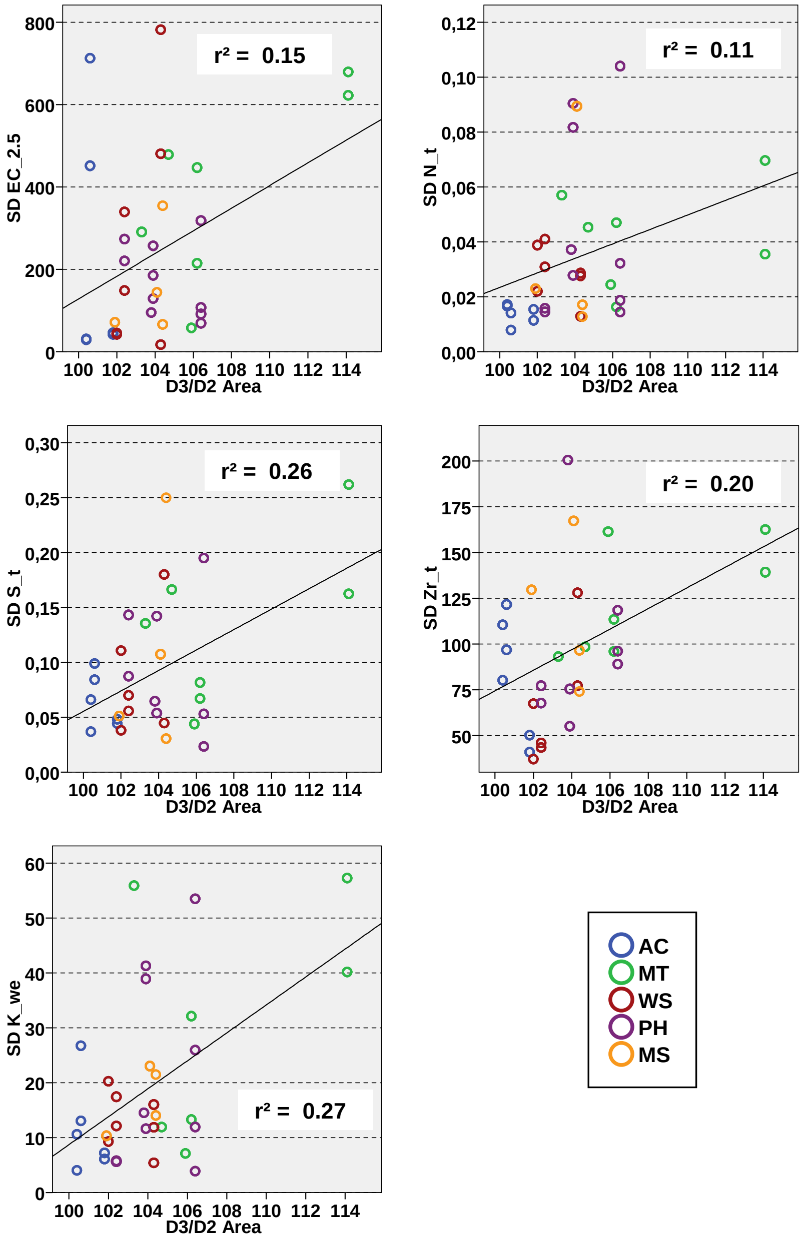


Fig. A.20: Correlation between surface roughness percentage and the standard deviation of selected parameters within each D3-unit.

B Appendix for Gellap and Nabaos

B.1 Reference Profiles

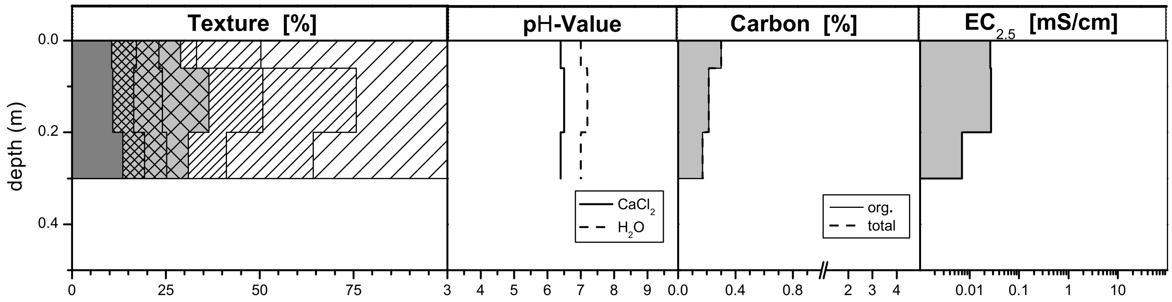


Fig. B.21: Reference profile for Old Accumulation-unit on Gellap, Sedimentation Area (G-SE-AO): BIOTA-profile P1337: Epileptic Regosol.

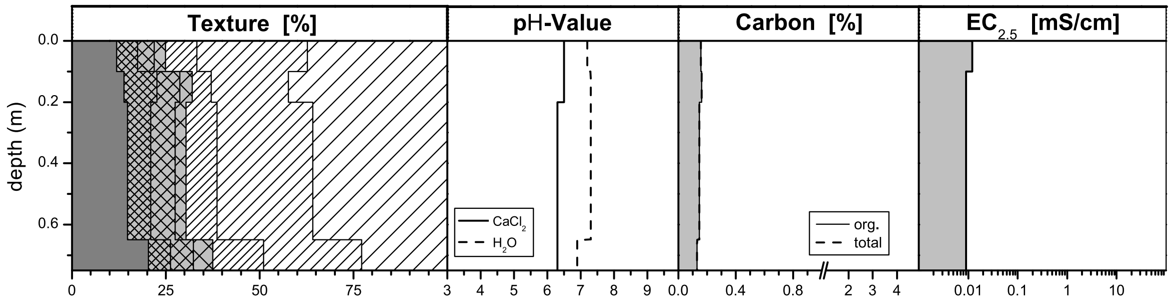
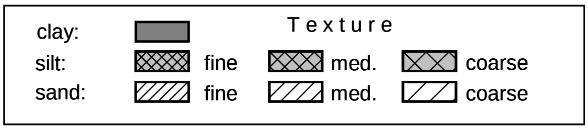


Fig. B.22: Reference profile for Young Accumulation-unit on Gellap, Sedimentation Area (G-SE-AY): BIOTA-profile P1335: Haplic Regosol.



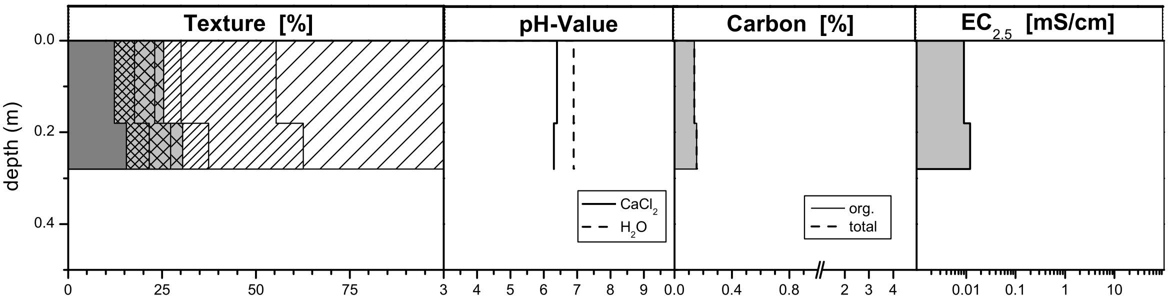


Fig. B.23: Reference profile for Rivier-unit on Gellap, Sedimentation Area (G-SE-RV): BIOTA-profile P1324: Epileptic Regosol.

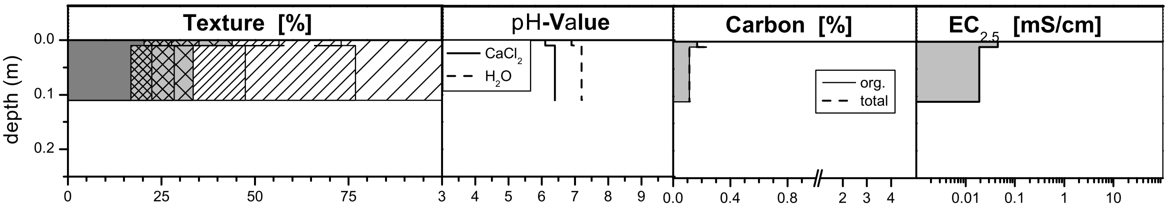
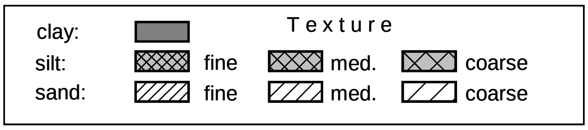


Fig. B.24: Reference profile for Brown Ridge-unit (South) on Gellap, Outcrop Area (G-OC-BS): BIOTA-profile P1333: Hyperskeletic Leptosol.



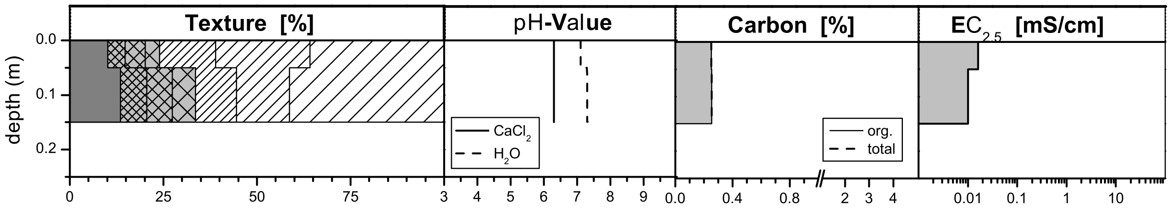


Fig. B.25: Reference profile for Rivier-unit on Gellap, Outcrop Area (G-OC-RV): BIOTA-profile P1331: Haplic Leptosol.

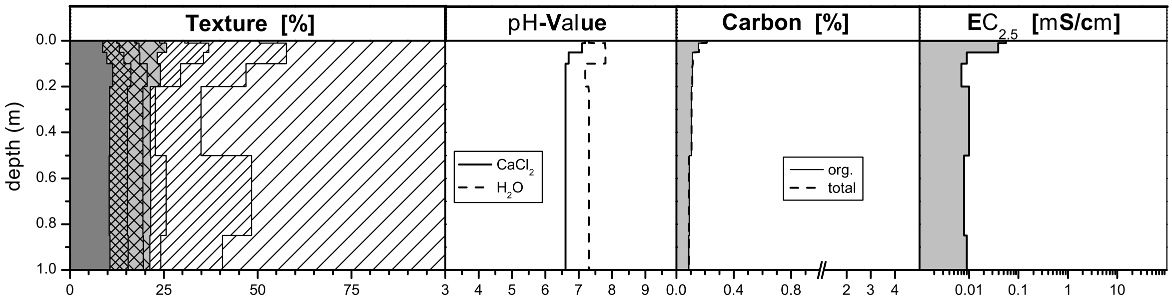
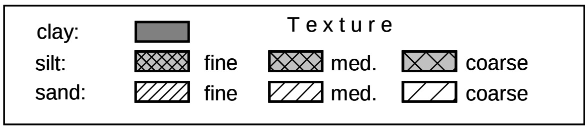


Fig. B.26: Reference profile for Old Accumulation-unit on Nabaos, Sedimentation Area (N-SE-AO): BIOTA-profile P1270: Haplic Regosol.



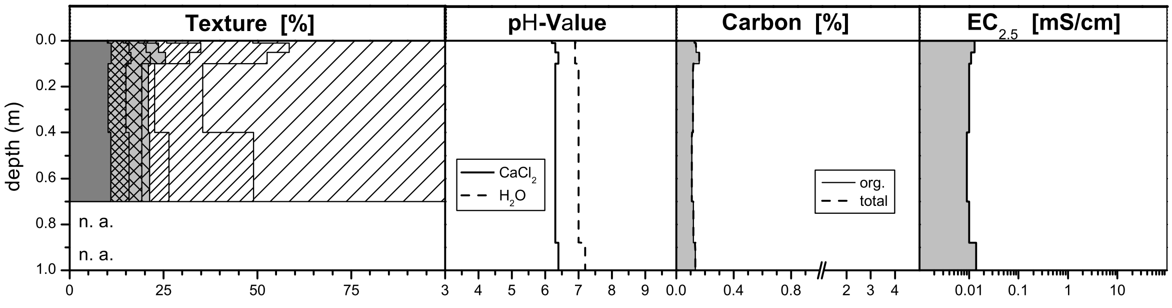


Fig. B.27: Reference profile for Young Accumulation-unit on Nabaos, Sedimentation Area (N-SE-AY): BIOTA-profile P1290: Haplic Regosol.

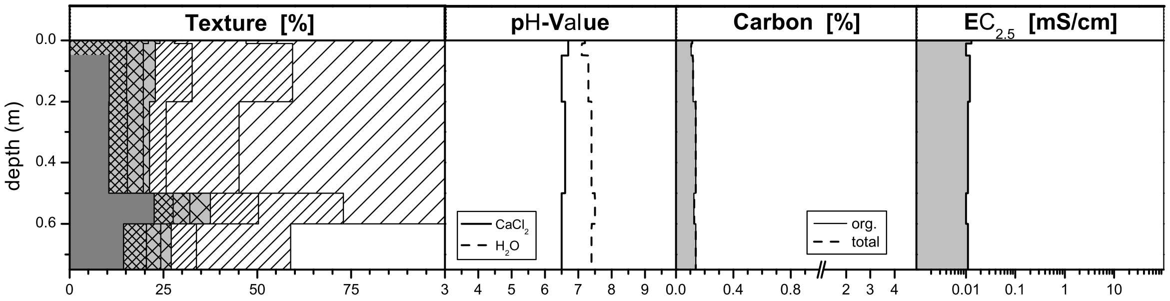
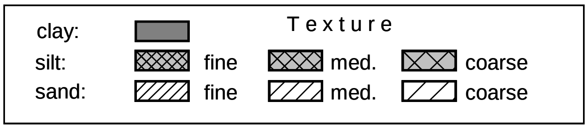


Fig. B.28: Reference profile for Rivier-unit on Nabaos, Sedimentation Area (N-SE-RV): BIOTA-profile P1286: Haplic Regosol.



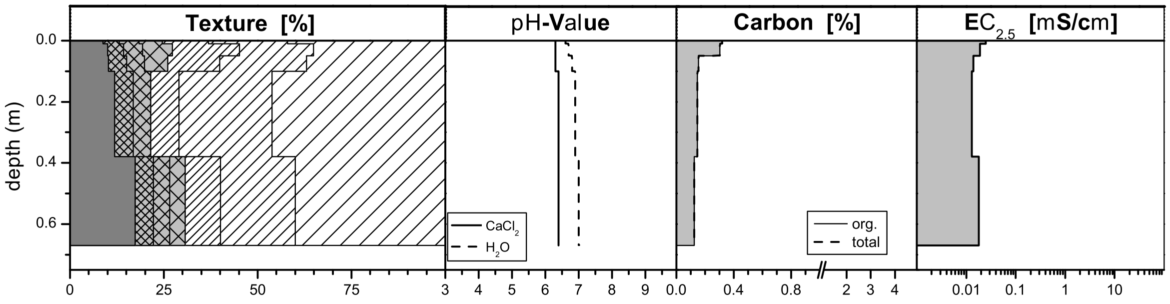


Fig. B.29: Reference profile for Rivier Island-unit on Nabaos, Sedimentation Area (N-SE-RI): BIOTA-profile P1291: Haplic Regosol.

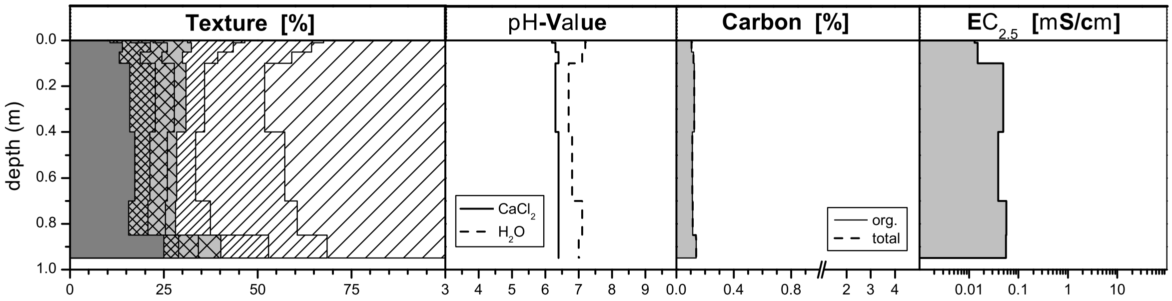
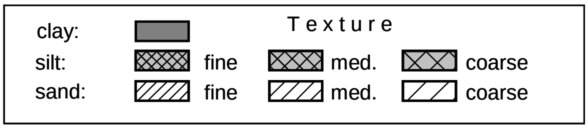


Fig. B.30: Reference profile for Brown Ridge-unit (South) on Nabaos, Outcrop Area (N-OC-BS): BIOTA-profile P1338: Haplic Regosol.



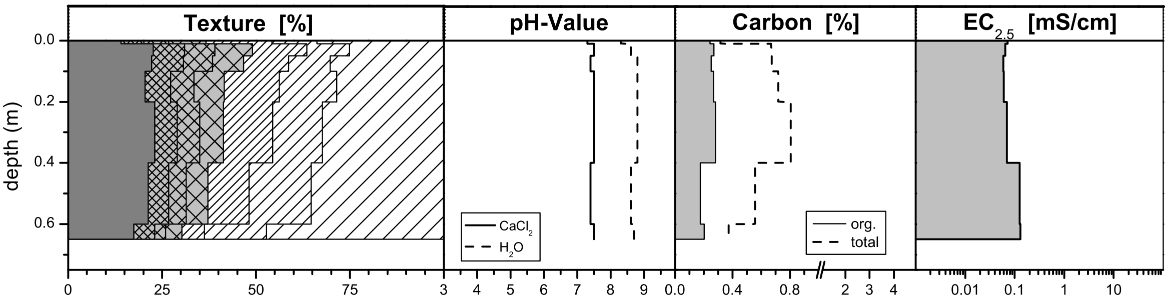


Fig. B.31: Reference profile for Brown Ridge -unit (North) on Nabaos, Outcrop Area (N-OC-BN): BIOTA-profile P1378: Haplic Regosol.

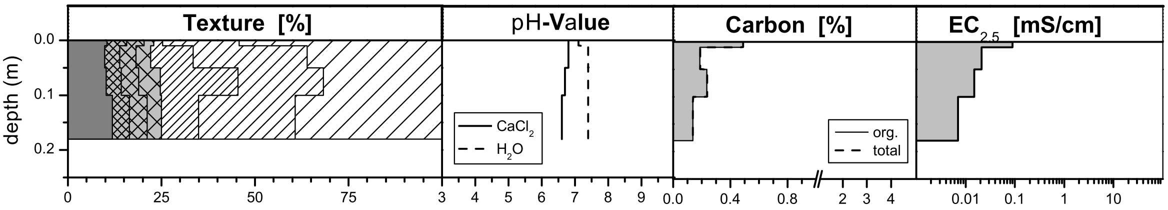


Fig. B.32: Reference profile for Rivier Island-unit (South) on Nabaos, Outcrop Area (N-OC-RI): BIOTA-profile P1377: Haplic Leptosol.

	Texture		
clay:	■		
silt:	▩ fine	▩ med.	▨ coarse
sand:	▨ fine	▨ med.	▨ coarse

B.2 Comparison of further Chemical Soil Parameters with the BIOTA-Transect Data Set

Miniprofile Data Gellap

Parameter	N	Min.	Perc. 25	Median	Mean	Perc. 75	Max.	SD
Cl_{we} (mg/l)	69	1	1	2	15	5	222	40
F_{we} (mg/l)	69	0.00	0.10	0.10	0.12	0.10	2.20	0.26
Br_{we} (mg/l)	69	0.00	0.00	0.00	0.07	0.10	1.30	0.19
NO_{3we} (mg/l)	69	0	12	34	97	91	1,334	192
NO_{2we} (mg/l)	69	0.3	0.3	0.4	0.7	0.6	4.7	0.8
SO_{4we} (mg/l)	69	1	2	6	25	20	370	55
HCO_{3we} (mg/l)	0							
Ca_{we} (mg/l)	69	6	10	17	31	31	323	46
Mg_{we} (mg/l)	69	2	4	6	11	10	98	15
K_{we} (mg/l)	69	2	5	10	13	17	76	12
Na_{we} (mg/l)	69	1	2	3	16	8	233	40
Fe_{we} (mg/l)	69	0.0	1.2	2.9	6.6	7.8	57.7	9.6
$Anions_{we}$ (mg/l)	0							
$Cations_{we}$ (mg/l)	0							

Transect Data

Parameter	N	Min.	Perc. 25	Median	Mean	Perc. 75	Max.	SD
Cl_{we} (mg/l)	1,629	0	2	6	294	25	34,477	1,517
F_{we} (mg/l)	1,461	0.00	0.10	0.20	0.43	0.40	21.90	1.13
Br_{we} (mg/l)	1,479	0.00	0.00	0.00	0.66	0.00	67.90	3.33
NO_{3we} (mg/l)	1,577	0	1	7	66	21	12,437	509
NO_{2we} (mg/l)	1,528	0.0	0.0	0.1	0.9	0.5	59.6	3.0
SO_{4we} (mg/l)	1,626	0	3	5	105	17	4176	377
HCO_{3we} (mg/l)	1,178	0	28	89	147	148	10,609	454
Ca_{we} (mg/l)	1,628	0	7	17	66	34	3568	204
Mg_{we} (mg/l)	1,627	0	3	7	31	14	1530	112
K_{we} (mg/l)	1,631	0	5	11	19	22	788	32
Na_{we} (mg/l)	1,632	0	1	5	154	33	20,680	828
Fe_{we} (mg/l)	851	0.0	0.8	4.4	17.6	16.0	418.3	39.5
$Anions_{we}$ (mg/l)	1,183	0.1	0.3	0.6	14.7	2.9	1,041	55.4
$Cations_{we}$ (mg/l)	1,181	0.0	1.6	2.7	16.1	6.2	1,100	55.8

Tab. B.4: Comparison of statistic measures of salt driven parameters between the miniprofile data set of Gellap and the BIOTA-transect data soil data set

Miniprofile Data Nabaos

Parameter	N	Min.	Perc. 25	Median	Mean	Perc. 75	Max.	SD
Cl_{we} (mg/l)	84	0	1	1	3	2	74	10
F_{we} (mg/l)	84	0.00	0.10	0.20	0.18	0.20	0.90	0.14
Br_{we} (mg/l)	84	0.00	0.00	0.00	0.03	0.00	2.10	0.23
NO_{3we} (mg/l)	84	0	0	2	44	10	1,716	206
NO_{2we} (mg/l)	84	0.0	0.2	0.2	0.4	0.3	4.2	0.7
SO_{4we} (mg/l)	84	1	1	3	18	6	487	71
HCO_{3we} (mg/l)	12	19	20	33	48	83	130	37
Ca_{we} (mg/l)	84	2	4	7	19	16	270	41
Mg_{we} (mg/l)	83	1	2	3	8	7	140	18
K_{we} (mg/l)	84	1	2	5	12	15	98	18
Na_{we} (mg/l)	84	1	1	2	3	4	22	3
Fe_{we} (mg/l)	84	0.0	0.9	2.3	5.1	7.2	49.0	7.2
$Anions_{we}$ (mg/l)	12	0.0	0.1	0.1	0.1	0.2	0	0.1
$Cations_{we}$ (mg/l)	12	0.4	0.4	0.7	0.9	1.5	2	0.6

Transect Data

Parameter	N	Min.	Perc. 25	Median	Mean	Perc. 75	Max.	SD
Cl_{we} (mg/l)	1,629	0	2	6	294	25	34,477	1,517
F_{we} (mg/l)	1,461	0.00	0.10	0.20	0.43	0.40	21.90	1.13
Br_{we} (mg/l)	1,479	0.00	0.00	0.00	0.66	0.00	67.90	3.33
NO_{3we} (mg/l)	1,577	0	1	7	66	21	12,437	509
NO_{2we} (mg/l)	1,528	0.0	0.0	0.1	0.9	0.5	59.6	3.0
SO_{4we} (mg/l)	1,626	0	3	5	105	17	4176	377
HCO_{3we} (mg/l)	1,178	0	28	89	147	148	10,609	454
Ca_{we} (mg/l)	1,628	0	7	17	66	34	3568	204
Mg_{we} (mg/l)	1,627	0	3	7	31	14	1530	112
K_{we} (mg/l)	1,631	0	5	11	19	22	788	32
Na_{we} (mg/l)	1,632	0	1	5	154	33	20,680	828
Fe_{we} (mg/l)	851	0.0	0.8	4.4	17.6	16.0	418.3	39.5
$Anions_{we}$ (mg/l)	1,183	0.1	0.3	0.6	14.7	2.9	1,041	55.4
$Cations_{we}$ (mg/l)	1,181	0.0	1.6	2.7	16.1	6.2	1,100	55.8

Tab. B.5: Comparison of statistic measures of salt driven parameters between the miniprofile data set of Nabaos and the BIOTA-transect data soil data set

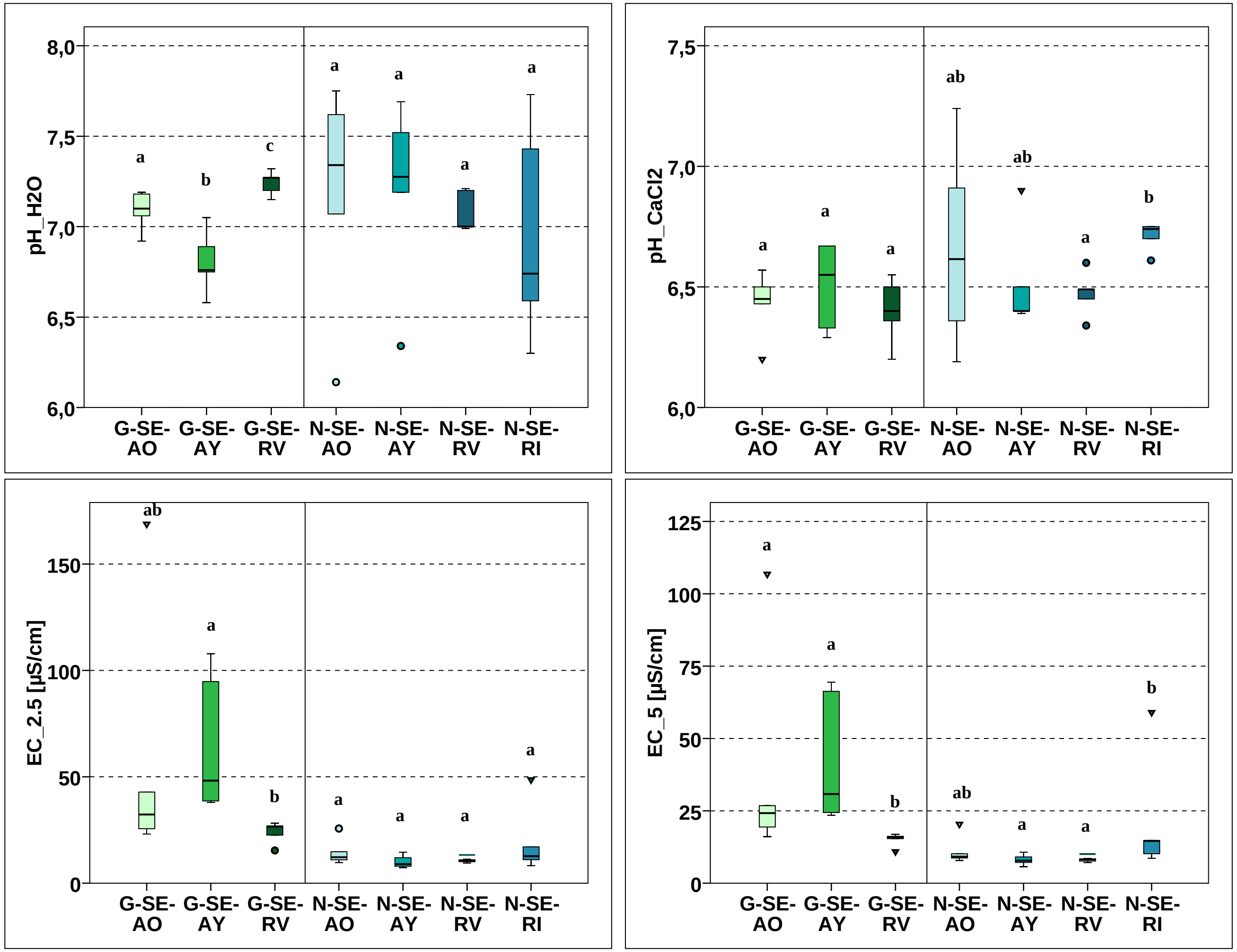


Fig. B.33: Comparison of D3-units of Sedimentation Area sites in Gellap and Nabaos (I): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Gellap sites in green colours, Nabaos sites in turquoise colours. Different letters indicate significant differences with p = 0.05.

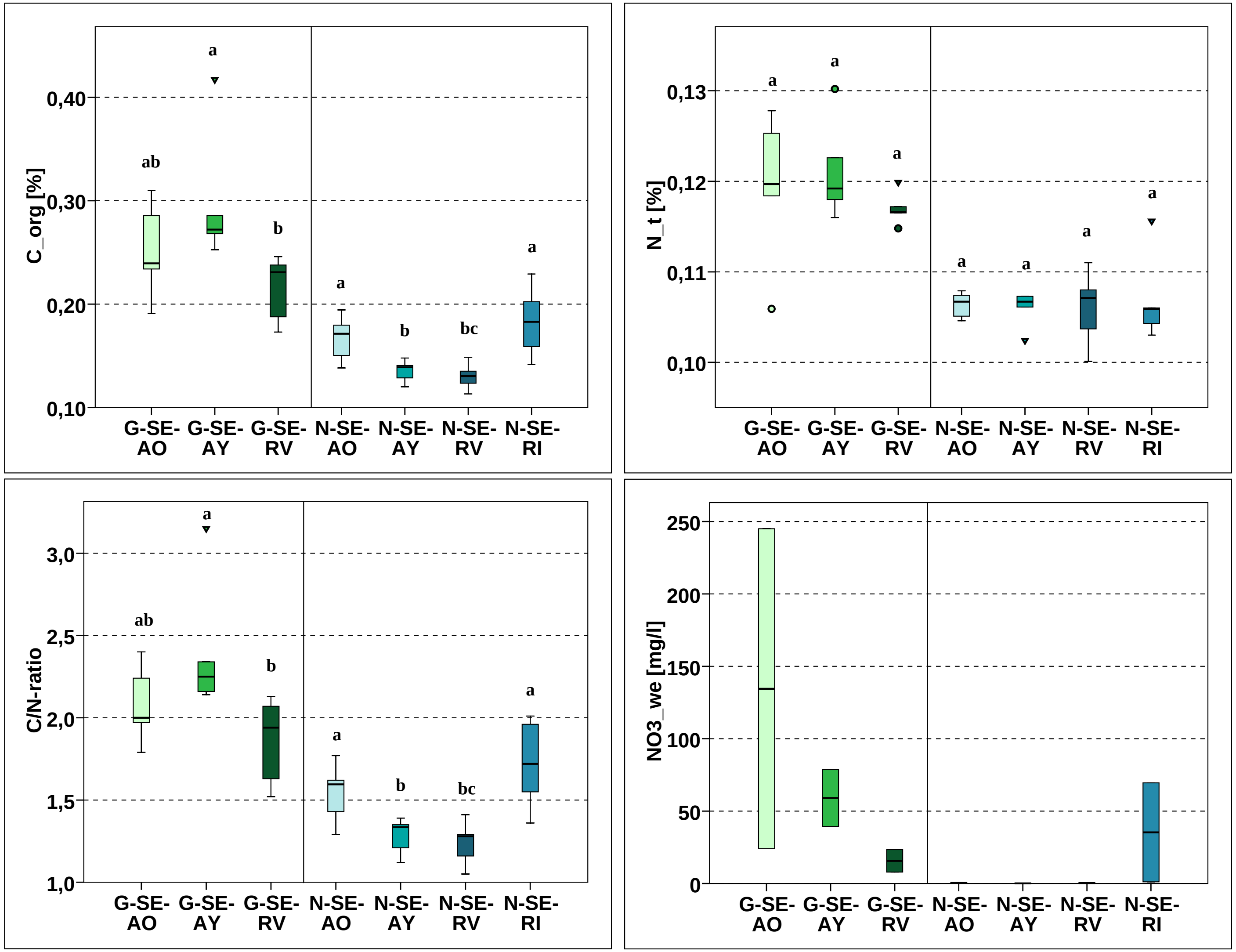


Fig. B.34: Comparison of D3-units of Sedimentation Area sites in Gellap and Nabaos (II): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Gellap sites in green colours, Nabaos sites in turquoise colours. Different letters indicate significant differences with p = 0.05.

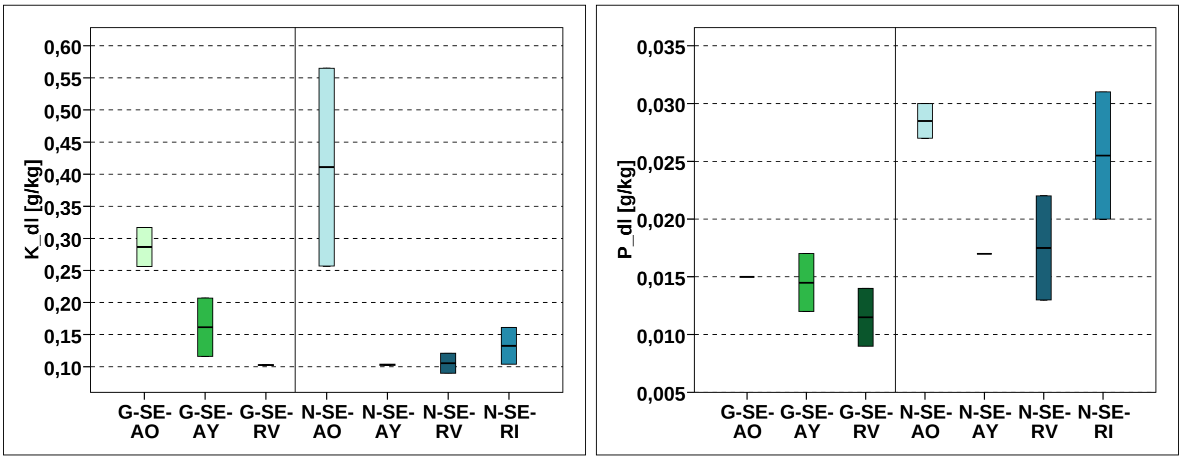


Fig. B.35: Comparison of D3-units of Sedimentation Area sites in Gellap and Nabaos (III): Range of K_{dl} and P_{dl}. Gellap sites in green colours, Nabaos sites in turquoise colours. Significance tests were omitted due to low samples numbers of partly < 5

	G-SE-AO		G-SE-AY		G-SE-RV	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH_{H2O}	5	7.1 ± 0.1 $^{(a)}$	5	6.8 ± 0.2 $^{(b)}$	5	7.2 ± 0.1 $^{(c)}$
pH_{CaCl2}	5	6.4 ± 0.1 $^{(a)}$	5	6.5 ± 0.2 $^{(a)}$	5	6.4 ± 0.1 $^{(a)}$
$EC_{2.5}$ [µS/cm]	5	59 ± 62 $^{(ab)}$	5	66 ± 33 $^{(a)}$	5	24 ± 5 $^{(b)}$
EC_5 [µS/cm]	5	39 ± 38 $^{(a)}$	5	43 ± 23 $^{(a)}$	5	15 ± 2 $^{(b)}$
C_{org} [%]	5	0.25 ± 0.05 $^{(ab)}$	5	0.30 ± 0.07 $^{(a)}$	5	0.22 ± 0.03 $^{(b)}$
N_t [%]	5	0.119 ± 0.008 $^{(a)}$	5	0.121 ± 0.006 $^{(a)}$	5	0.117 ± 0.002 $^{(a)}$
C/N-ratio	5	2.1 ± 0.2 $^{(ab)}$	5	2.4 ± 0.4 $^{(a)}$	5	1.9 ± 0.3 $^{(b)}$
K_{dl} [g/kg]	2	0.29 ± 0.04	2	0.16 ± 0.06	2	0.10 ± <0.01
P_{dl} [g/kg]	2	0.015 ± <0.001	2	0.015 ± 0.004	2	0.012 ± 0.004
S_t [g/kg]	5	0.10 ± 0.03 $^{(a)}$	5	0.10 ± 0.02 $^{(a)}$	5	0.07 ± <0.01 $^{(b)}$
Si_t [%]	5	34.74 ± 0.23 $^{(a)}$	5	34.73 ± 0.22 $^{(a)}$	5	35.06 ± 0.11 $^{(a)}$
Al_t [%]	5	7.47 ± 0.14 $^{(a)}$	5	7.48 ± 0.19 $^{(a)}$	5	7.30 ± 0.10 $^{(a)}$
Na_t [g/kg]	5	6.15 ± 0.34 $^{(a)}$	5	6.01 ± 0.23 $^{(a)}$	5	5.60 ± 0.13 $^{(b)}$
K_t [g/kg]	5	20.87 ± 0.56 $^{(a)}$	5	20.49 ± 0.21 $^{(a)}$	5	20.44 ± 0.32 $^{(a)}$
Ca_t [g/kg]	5	3.91 ± 0.20 $^{(ab)}$	5	4.19 ± 0.11 $^{(a)}$	5	3.79 ± 0.13 $^{(b)}$
Mg_t [g/kg]	5	6.77 ± 0.30 $^{(a)}$	5	6.63 ± 0.19 $^{(b)}$	5	6.32 ± 0.10 $^{(ab)}$
P_t [g/kg]	5	0.44 ± 0.02 $^{(a)}$	5	0.41 ± 0.01 $^{(b)}$	5	0.39 ± 0.01 $^{(c)}$
Ti_t [g/kg]	5	4.00 ± 0.07 $^{(a)}$	5	4.00 ± 0.08 $^{(a)}$	5	3.92 ± 0.10 $^{(a)}$
Fe_t [g/kg]	5	33.93 ± 0.23 $^{(a)}$	5	33.72 ± 0.43 $^{(a)}$	5	34.05 ± 0.45 $^{(a)}$
Mn_t [g/kg]	5	0.37 ± 0.01 $^{(a)}$	5	0.35 ± 0.01 $^{(b)}$	5	0.33 ± 0.01 $^{(c)}$
Zn_t [mg/kg]	5	82.4 ± 0.9 $^{(a)}$	5	75.8 ± 0.7 $^{(b)}$	5	76.7 ± 0.6 $^{(b)}$

Tab. B.6: Comparison of D3-units on the Gellap Sedimentation site. Boxplots are based on weighted means over 0-10 cm for each miniprofile. Different letters indicate significant differences at $p < 0.05$.

	N-SE-AO		N-SE-AY		N-SE-RV		N-SE-RI	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH_{H2O}	6	7.2 ± 0.6 $^{(a)}$	6	7.2 ± 0.5 $^{(a)}$	5	7.1 ± 0.1 $^{(a)}$	5	7.0 ± 0.6 $^{(a)}$
pH_{CaCl2}	6	6.7 ± 0.4 $^{(ab)}$	6	6.5 ± 0.2 $^{(ab)}$	5	6.5 ± 0.1 $^{(a)}$	5	6.7 ± 0.1 $^{(b)}$
$EC_{2.5}$ [µS/cm]	6	14 ± 6 $^{(a)}$	6	10 ± 3 $^{(a)}$	5	11 ± 1 $^{(a)}$	5	20 ± 17 $^{(a)}$
EC_5 [µS/cm]	6	11 ± 5 $^{(ab)}$	6	8 ± 2 $^{(a)}$	5	8 ± 1 $^{(a)}$	5	21 ± 21 $^{(b)}$
C_{org} [%]	6	0.17 ± 0.02 $^{(a)}$	6	0.14 ± 0.01 $^{(b)}$	5	0.13 ± 0.01 $^{(bc)}$	5	0.18 ± 0.03 $^{(a)}$
N_t [%]	6	0.106 ± 0.001 $^{(a)}$	6	0.106 ± 0.002 $^{(a)}$	5	0.106 ± 0.004 $^{(a)}$	5	0.107 ± 0.005 $^{(a)}$
C/N-ratio	6	1.6 ± 0.2 $^{(a)}$	6	1.3 ± 0.1 $^{(b)}$	5	1.2 ± 0.1 $^{(bc)}$	5	1.7 ± 0.3 $^{(a)}$
K_{dl} [g/kg]	2	0.41 ± 0.22	2	0.10 ± <0.01	2	0.11 ± 0.02	2	0.13 ± 0.04
P_{dl} [g/kg]	2	0.029 ± 0.002	2	0.017 ± <0.001	2	0.018 ± 0.006	2	0.026 ± 0.008

Tab. B.7: Comparison of D3-units on the Nabaos Sedimentation site. Boxplots are based on weighted means over 0-10 cm for each miniprofile. Different letters indicate significant differences at $p < 0.05$.

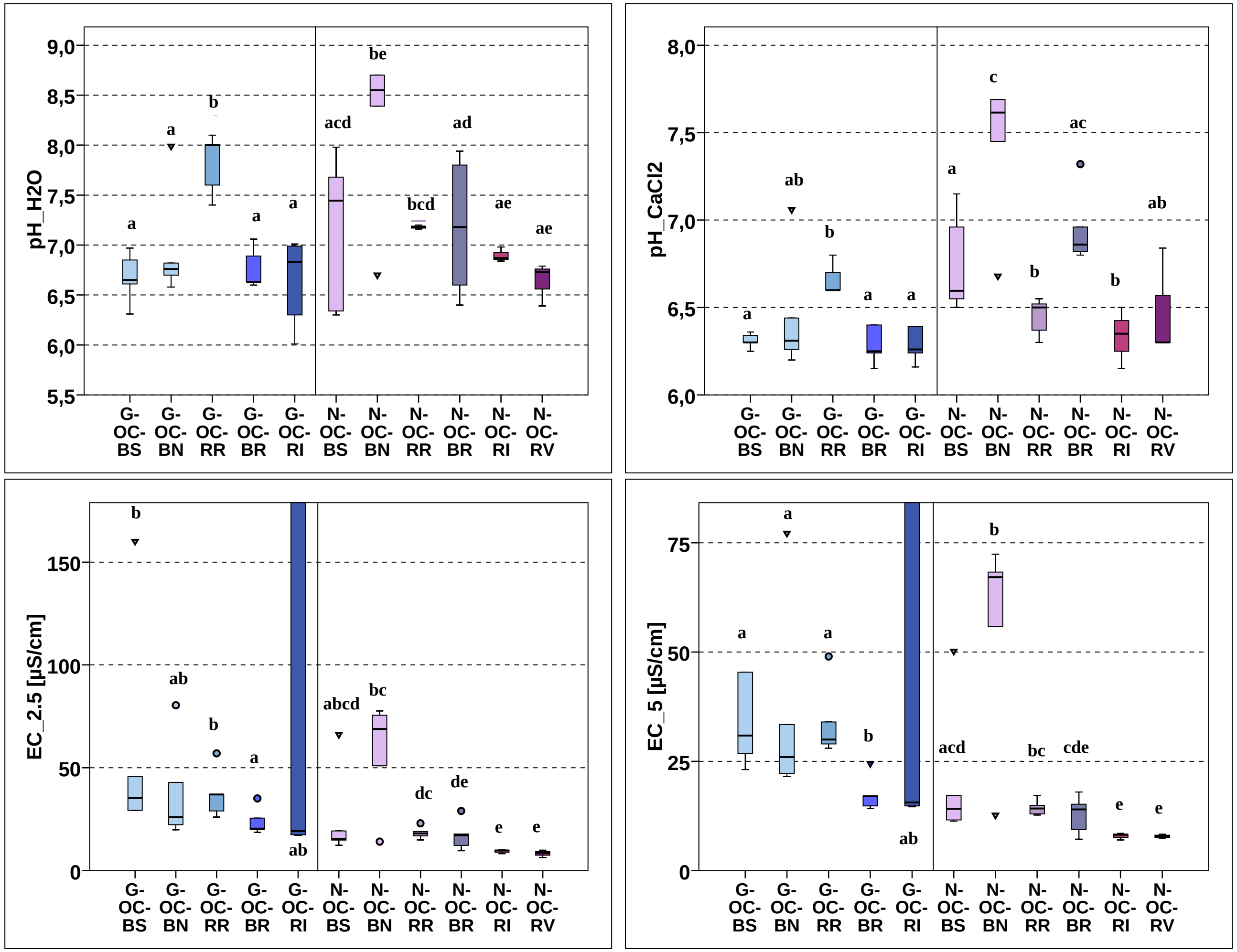


Fig. B.36: Comparison of D3-units of Outcrop Area sites in Gellap and Nabaos (I): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Gellap sites in blue, Nabaos sites in violett colours. Different letters indicate significant differences with p = 0.05.

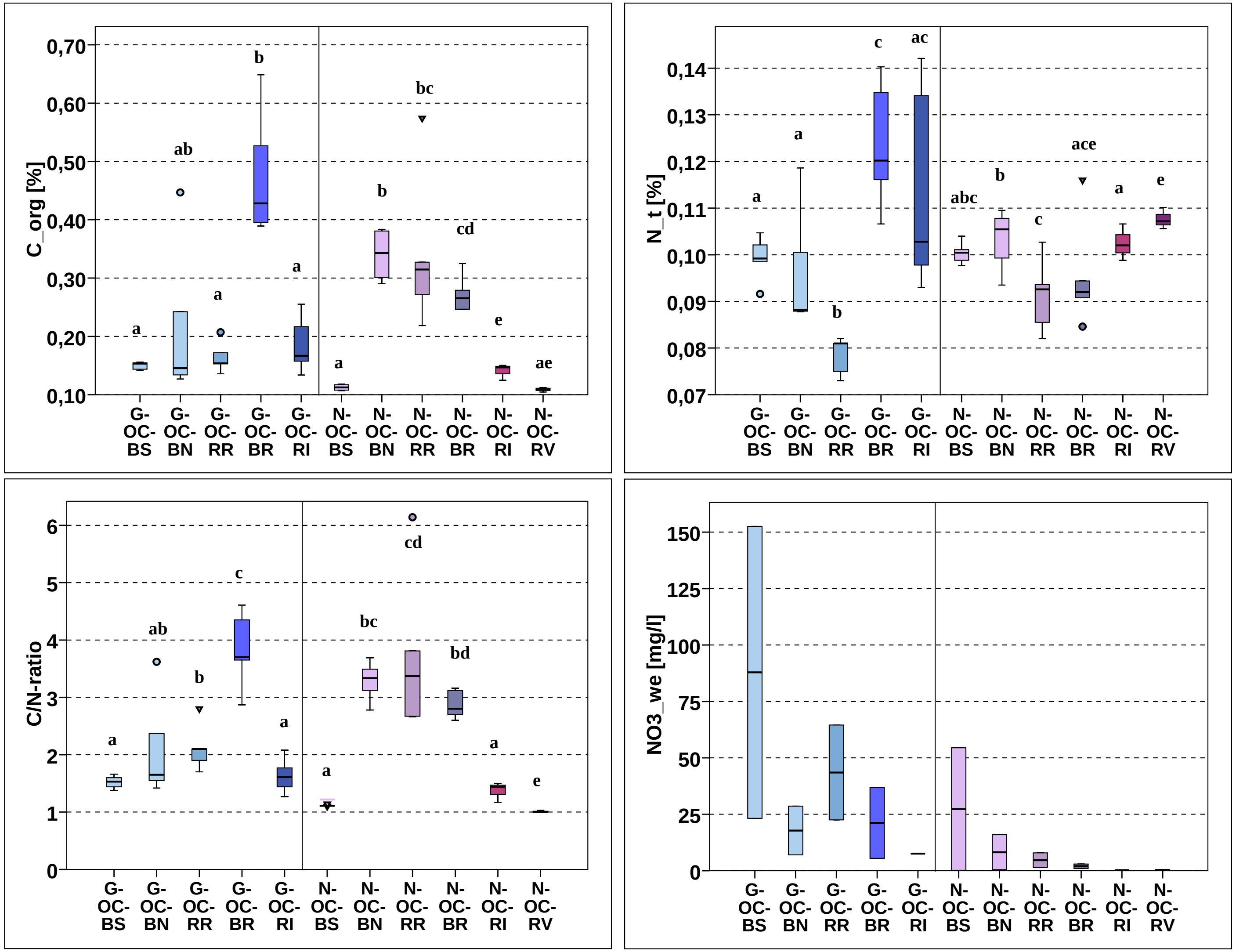


Fig. B.37: Comparison of D3-units of Outcrop Area sites in Gellap and Nabaos (II): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Gellap sites in blue colours, Nabaos sites in violett colours. Different letters indicate significant differences with p =.

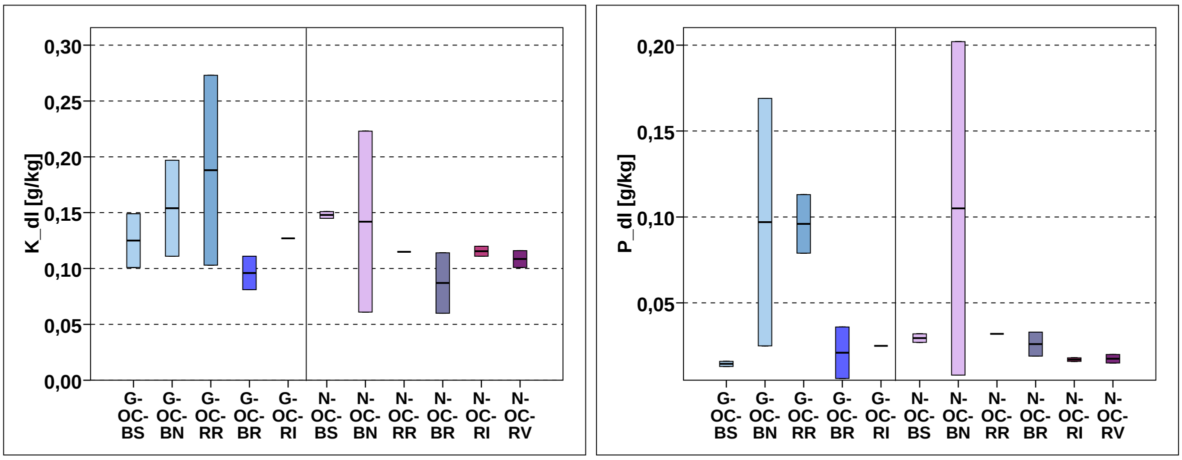


Fig. B.38: Comparison of D3-units of Outcrop Area sites in Gellap and Nabaos (III): Range of K_{dl} and P_{dl}. Gellap sites in blue colours, Nabaos sites in violett colours. Significance tests were omitted due to low samples numbers of partly < 5.

	G-OC-BS		**G-OC-BN**		**G-OC-RR**		**G-OC-BR**		**G-OC-RI**	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH$_{\mathrm{H2O}}$	5	6.7 ± 0.3 $^{(a)}$	5	7 ± 0.6 $^{(a)}$	5	7.8 ± 0.3 $^{(b)}$	5	6.8 ± 0.2 $^{(a)}$	5	6.6 ± 0.4 $^{(a)}$
pH$_{\mathrm{CaCl2}}$	5	6.3 ± <0.1 $^{(a)}$	5	6.5 ± 0.4 $^{(ab)}$	5	6.7 ± 0.1 $^{(b)}$	5	6.3 ± 0.1 $^{(a)}$	5	6.3 ± 0.1 $^{(a)}$
EC$_{2.5}$ [µS/cm]	5	60 ± 56 $^{(b)}$	5	38 ± 25 $^{(ab)}$	5	37 ± 12 $^{(b)}$	5	24 ± 7 $^{(a)}$	5	358 ± 466 $^{(ab)}$
EC$_{5}$ [µS/cm]	5	55 ± 53 $^{(a)}$	5	36 ± 23 $^{(a)}$	5	34 ± 9 $^{(a)}$	5	18 ± 4 $^{(b)}$	5	268 ± 348 $^{(ab)}$
C$_{\mathrm{org}}$ [%]	5	0.15 ± 0.01 $^{(a)}$	5	0.22 ± 0.14 $^{(ab)}$	5	0.16 ± 0.03 $^{(a)}$	5	0.48 ± 0.11 $^{(b)}$	5	0.19 ± 0.05 $^{(a)}$
N$_{t}$ [%]	5	0.099 ± 0.005 $^{(a)}$	5	0.097 ± 0.013 $^{(a)}$	5	0.078 ± 0.004 $^{(b)}$	5	0.124 ± 0.014 $^{(c)}$	5	0.114 ± 0.022 $^{(ac)}$
C/N-ratio	5	1.5 ± 0.1 $^{(a)}$	5	2.1 ± 0.9 $^{(ab)}$	5	2.1 ± 0.4 $^{(b)}$	5	3.8 ± 0.7 $^{(c)}$	5	1.6 ± 0.3 $^{(a)}$
K$_{\mathrm{dl}}$ [g/kg]	2	0.13 ± 0.03	2	0.15 ± 0.06	2	0.19 ± 0.12	2	0.10 ± 0.02	1	0. 13
P$_{\mathrm{dl}}$ [g/kg]	2	0.015 ± 0.002	2	0.097 ± 0.102	2	0.096 ± 0.024	2	0.021 ± 0.021	1	0.025
S$_{t}$ [g/kg]	5	0.12 ± 0.03 $^{(ab)}$	5	0.11 ± 0.03 $^{(ab)}$	5	0.13 ± 0.01 $^{(a)}$	5	0.11 ± 0.01 $^{(b)}$	5	0.14 ± 0.07 $^{(ab)}$
Si$_{t}$ [%]	5	34.65 ± 0.06 $^{(a)}$	5	34.74 ± 0.65 $^{(ab)}$	5	34.01 ± 0.26 $^{(b)}$	5	34.19 ± 0.26 $^{(bc)}$	5	34.68 ± 0.42 $^{(ac)}$
Al$_{t}$ [%]	5	7.48 ± 0.05 $^{(ab)}$	5	7.34 ± 0.23 $^{(ab)}$	5	7.26 ± 0.23 $^{(a)}$	5	7.85 ± 0.46 $^{(b)}$	5	7.52 ± 0.38 $^{(ab)}$
Na$_{t}$ [g/kg]	5	5.57 ± 0.31 $^{(a)}$	5	5.92 ± 0.45 $^{(a)}$	5	6.09 ± 0.63 $^{(a)}$	5	6.59 ± 0.86 $^{(a)}$	5	5.70 ± 0.54 $^{(a)}$
K$_{t}$ [g/kg]	5	20.29 ± 0.71 $^{(a)}$	5	19.45 ± 0.52 $^{(ab)}$	5	19.05 ± 0.78 $^{(b)}$	5	19.33 ± 1.48 $^{(ab)}$	5	19.31 ± 0.95 $^{(ab)}$
Ca$_{t}$ [g/kg]	5	4.10 ± 0.49 $^{(a)}$	5	5.77 ± 2.10 $^{(bc)}$	5	6.60 ± 0.61 $^{(b)}$	5	5.26 ± 1.17 $^{(abc)}$	5	4.54 ± 0.41 $^{(ac)}$
Mg$_{t}$ [g/kg]	5	7.13 ± 0.05 $^{(ac)}$	5	7.39 ± 0.76 $^{(abc)}$	5	8.12 ± 0.20 $^{(b)}$	5	6.95 ± 0.65 $^{(c)}$	5	7.05 ± 0.48 $^{(c)}$
P$_{t}$ [g/kg]	5	0.40 ± 0.01 $^{(a)}$	5	0.43 ± 0.07 $^{(a)}$	5	0.74 ± 0.12 $^{(b)}$	5	0.40 ± 0.03 $^{(a)}$	5	0.39 ± 0.03 $^{(a)}$
Ti$_{t}$ [g/kg]	5	4.07 ± 0.09 $^{(ade)}$	5	3.90 ± 0.07 $^{(b)}$	5	5.12 ± 0.26 $^{(c)}$	5	4.24 ± 0.18 $^{(d)}$	5	3.88 ± 0.22 $^{(be)}$
Fe$_{t}$ [g/kg]	5	36.20 ± 0.49 $^{(a)}$	5	34.11 ± 0.61 $^{(be)}$	5	42.57 ± 1.56 $^{(c)}$	5	33.10 ± 3.04 $^{(e)}$	5	35.01 ± 0.69 $^{(e)}$
Mn$_{t}$ [g/kg]	5	0.39 ± 0.02 $^{(a)}$	5	0.38 ± 0.05 $^{(a)}$	5	1.36 ± 0.30 $^{(b)}$	5	0.55 ± 0.04 $^{(c)}$	5	0.36 ± 0.03 $^{(a)}$
Zn$_{t}$ [mg/kg]	5	77.9 ± 1.7 $^{(a)}$	5	81.4 ± 6.8 $^{(a)}$	5	111.2 ± 13.5 $^{(b)}$	5	78.6 ± 19.6 $^{(a)}$	5	78.9 ± 1.6 $^{(a)}$

Tab. B.8: Comparison of D3-units on the Gellap Outcrop site. Data are weighted means and standard deviations calculated for 0-10 cm for each miniprofile. Different letters indicate significant differences at $p < 0.05$.

	N-OC-BS		**N-OC-BN**		**N-OC-RR**		**N-OC-BR**		**N-OC-RI**		**N-OC-RV**	
	n	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**	**n**	**mean ± SD**
pH$_{H2O}$	6	7.2 ± 0.7 $^{(acd)}$	6	8.3 ± 0.8 $^{(be)}$	5	7.2 ± <0.1 $^{(bcd)}$	5	7.2 ± 0.7 $^{(ad)}$	3	6.9 ± 0.1 $^{(ae)}$	3	6.6 ± 0.2 $^{(ae)}$
pH$_{CaCl2}$	6	6.7 ± 0.3 $^{(a)}$	6	7.5 ± 0.4 $^{(c)}$	5	6.4 ± 0.1 $^{(b)}$	5	7.0 ± 0.2 $^{(ac)}$	3	6.3 ± 0.2 $^{(b)}$	3	6.5 ± 0.3 $^{(ab)}$
EC$_{2.5}$ [µS/cm]	6	24 ± 21 $^{(abcd)}$	6	59 ± 24 $^{(bc)}$	5	18 ± 3 $^{(dc)}$	5	17 ± 7 $^{(de)}$	3	9 ± 1 $^{(e)}$	3	8 ± 2 $^{(e)}$
EC$_5$ [µS/cm]	6	20 ± 15 $^{(acd)}$	6	57 ± 23 $^{(b)}$	5	14 ± 2 $^{(bc)}$	5	13 ± 4 $^{(cde)}$	3	8 ± 1 $^{(e)}$	3	8 ± 1 $^{(e)}$
C$_{org}$ [%]	6	0.11 ± <0.01 $^{(a)}$	6	0.34 ± 0.04 $^{(b)}$	5	0.34 ± 0.14 $^{(bc)}$	5	0.27 ± 0.03 $^{(cd)}$	3	0.14 ± 0.01 $^{(e)}$	3	0.11 ± <0.01 $^{(ae)}$
N$_t$ [%]	6	0.100 ± 0.002 $^{(abc)}$	6	0.104 ± 0.006 $^{(be)}$	5	0.091 ± 0.008 $^{(c)}$	5	0.096 ± 0.012 $^{(ace)}$	3	0.102 ± 0.004 $^{(ace)}$	3	0.108 ± 0.002 $^{(e)}$
C/N-ratio	6	1.1 ± <0.1 $^{(a)}$	6	3.3 ± 0.3 $^{(bc)}$	5	3.7 ± 1.4 $^{(cd)}$	5	2.9 ± 0.3 $^{(bd)}$	3	1.4 ± 0.2 $^{(ae)}$	3	1.0 ± <0.1 $^{(e)}$
K$_{dl}$ [g/kg]	2	0.15 ± <0.01	2	0.14 ± 0.11	1	0.12	2	0.09 ± 0.04	2	0.12 ± 0.01	2	0.11 ± 0.01
P$_{dl}$ [g/kg]	2	0.030 ± 0.004	2	0.105 ± 0.137	1	0.032	2	0.026 ± 0.010	2	0.017 ± 0.001	2	0.018 ± 0.004

Tab. B.9: Comparison of D3-units on the Nabaos Outcrop site. Data are weighted means and standard deviations calculated for 0-10 cm for each miniprofile. Different letters indicate significant differences at $p < 0.05$.

B.5 Comparison of Total Element Contents on D3-Sites in Gellap

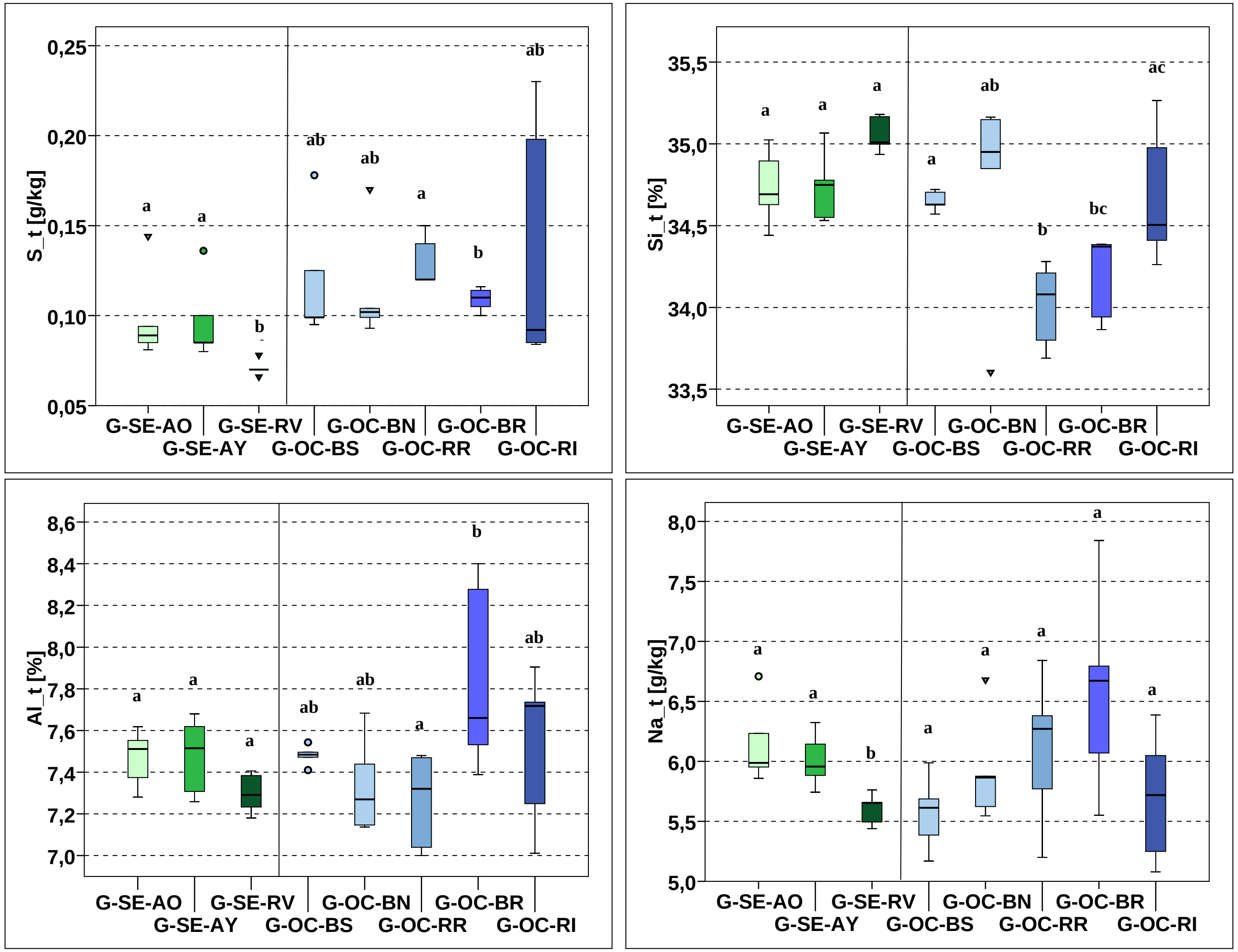


Fig. B.39: Comparison of selected total element contents on D3-units of Gellap (I): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Sedimentation site units in green colours, Outcrop-Site units in blue colours. Different letters indicate significant differences with $p = 0.05$.

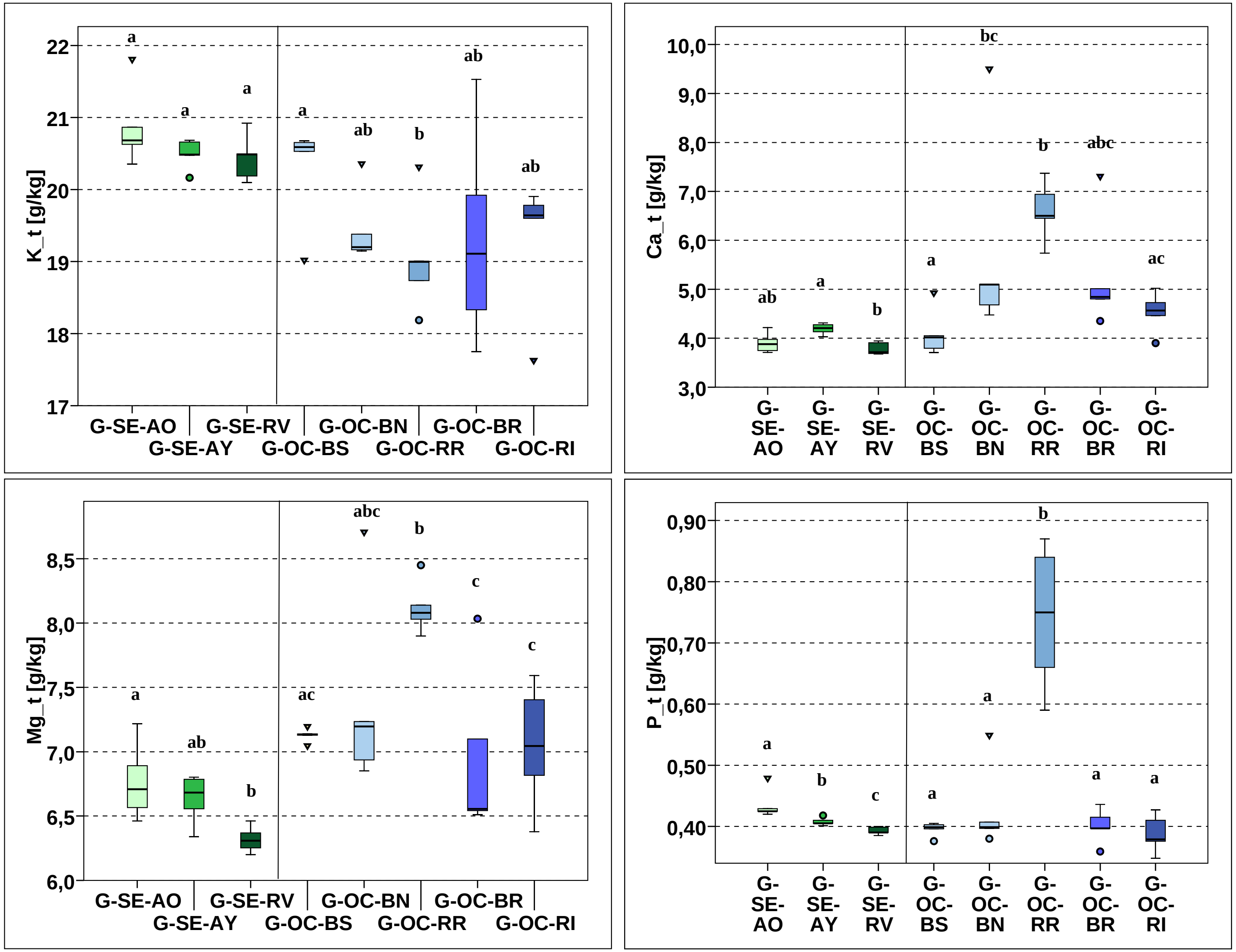


Fig. B.40: Comparison of selected total element contents on D3-units of Gellap (II): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Sedimentation site units in green colours, Outcrop-Site units in blue colours. Different letters indicate significant differences with p = 0.05.

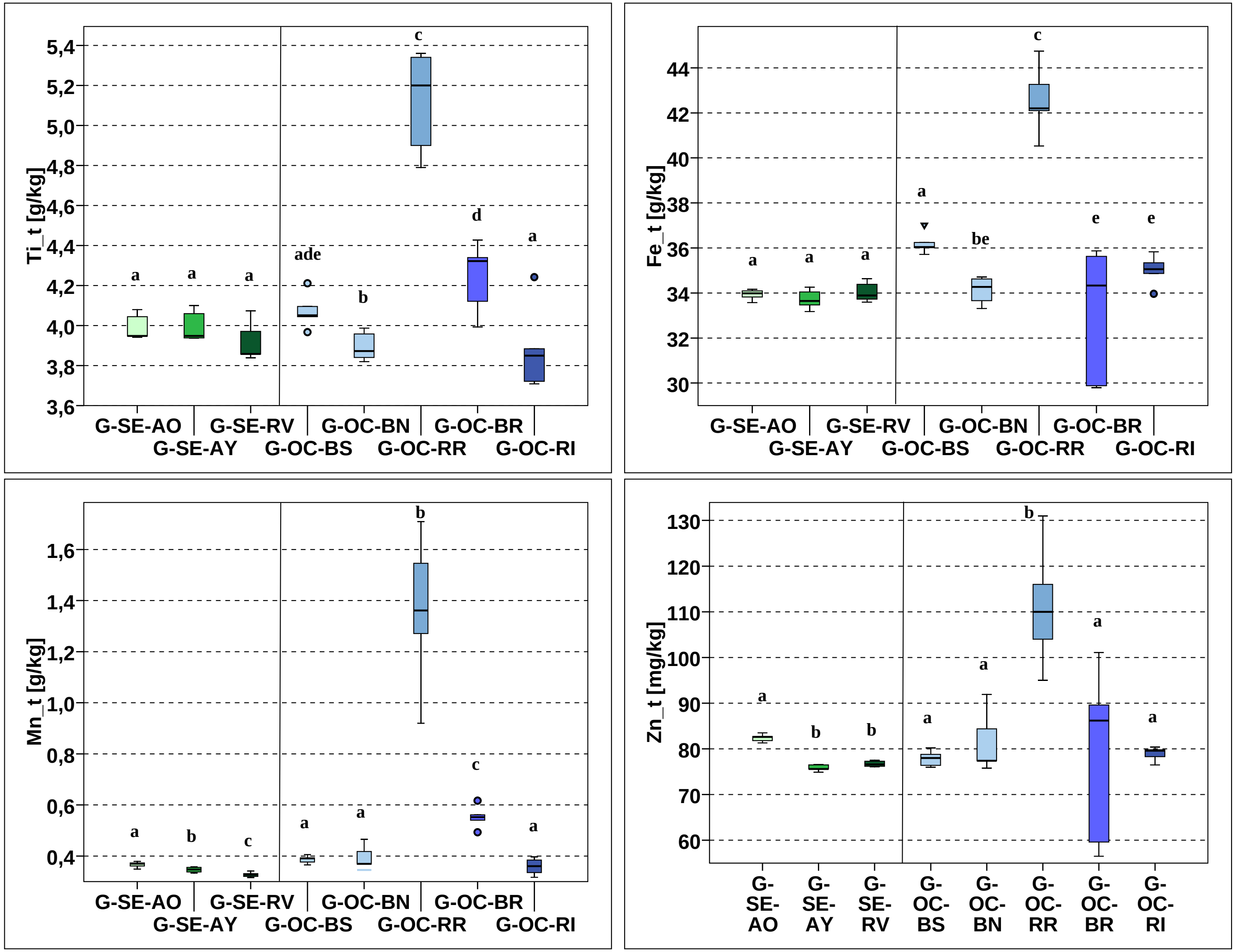


Fig. B.41: Comparison of selected total element contents on D3-units of Gellap (III): Boxplots are based on weighted means over 0-10 cm for each miniprofile. Sedimentation site units in green colours, Outcrop-Site units in blue colours. Different letters indicate significant differences with p = 0.05.

B.6 Comparison of Texture in Gellap and Nabaos

D4-unit	Layer	Clay	fSi	mSi	cSi	Silt	fSf	cSf
G-SE-AO-O	0-1	6.68	3.85	5.73	5.25	14.83	3.03	1.80
G-SE-AO-O	1-5	8.12	3.58	6.24	7.90	17.72	5.71	3.20
G-SE-AO-O	5-10	9.85	4.71	6.28	7.62	18.61	5.35	3.20
G-SE-AY-O	0-1	7.33	4.20	4.92	3.77	12.89	1.84	1.47
G-SE-AY-O	1-5	8.54	3.53	5.95	8.00	17.48	6.76	5.14
G-SE-AY-O	5-10	9.94	3.19	7.59	5.97	16.75	6.16	4.45
N-SE-AO-O	0-1	8.79	3.62	4.82	6.65	15.09	4.45	2.28
N-SE-AO-O	1-5	8.72	4.44	5.26	7.29	16.99	6.93	4.35
N-SE-AO-O	5-10	9.84	4.53	4.23	4.63	13.39	7.76	4.58
N-SE-AY-O	0-1	10.02	4.26	4.16	2.14	10.56	2.31	2.95
N-SE-AY-O	1-5	11.05	4.77	4.54	3.26	12.57	6.59	4.68
N-SE-AY-O	5-10	11.08	5.24	5.18	4.01	14.43	3.21	3.21

D4-unit	Layer	fS	mS	cS	Sand	text. class	Rock-fragments
G-SE-AO-O	0-1	4.83	18.72	54.92	78.47	Sl2	14.01
G-SE-AO-O	1-5	8.91	21.60	43.63	74.14	Sl2	8.56
G-SE-AO-O	5-10	8.55	21.05	41.93	71.53	Sl3	14.11
G-SE-AY-O	0-1	3.31	17.01	59.44	79.76	Sl2	20.60
G-SE-AY-O	1-5	11.90	24.94	37.21	74.05	Sl2	19.88
G-SE-AY-O	5-10	10.61	20.72	41.91	73.24	Sl3	21.97
N-SE-AO-O	0-1	6.73	19.80	49.53	76.06	Sl2	22.05
N-SE-AO-O	1-5	11.28	20.67	42.31	74.26	Sl2	23.65
N-SE-AO-O	5-10	12.34	22.09	42.31	76.74	Sl3	27.81
N-SE-AY-O	0-1	5.26	22.90	51.27	79.43	St2	30.68
N-SE-AY-O	1-5	11.27	23.59	41.53	76.39	Sl3	28.80
N-SE-AY-O	5-10	6.42	20.70	47.33	74.45	Sl3	26.20

Tab. B.10: Comparison of texture analysis of the D3-units Old Accumulation Area (AO) and Young Accumulation (AY) Area of the Sedimentation Areas in Gellap and Nabaos.

B.7 Further Tables on Infiltration and Microtopography

Particle class	**R**	**Particle class**	**R**
clay	-0.66		
silt	-0.52	fine silt	-0.33
		middle silt	-0.28
		coarse silt	-0.61
sand	0.65	fine sand, total	-0.38
		finest fine sand	-0.48
		coarse fine sand	-0.07
		medium sand	0.58
		coarse sand	0.53
pebbles	-0.20		
clay + coarse silt	-0.77		
middle sand + coarse sand	0.70		

Tab. B.11: Coefficients of correlation between single ring infiltration rates and texture classes of the 1-5 layer in Shrub Canopy and Open Soil units of Gellap and Nabaos.

Parameter	**wm 0-10 cm**	**0-1 cm**	**1-5 cm**	**5-10 cm**
pH_{H2O}	0.25	**0.47** *	0.20	0.30
pH_{CaCl2}	0.38	**0.54** *	0.34	**0.46** *
$EC_{2.5}$	0.39	0.16	0.38	**0.43** *
EC_5	**0.44** *	0.35	**0.44** *	**0.47** *
C_{org}	0.14	0.28	0.12	0.35
N_t	0.16	0.20	0.12	**0.40** *
C/N-ratio	0.11	0.29	0.11	0.30
K_{dl}	-	**0.67** *	-	-
P_{dl}	-	0.37	-	-
S_t	0.44	0.41	**0.67** *	0.06
Si_t	-0.22	-0.13	-0.3	-0.11
Al_t	-0.03	-0.12	-0.01	0
Na_t	0.01	0.28	0.04	-0.06
K_t	0.11	-0.003	0.11	0.11
Ca_t	-0.31	0.02	-0.30	-0.29
Mg_t	0.14	0.27	-0.02	0.22
P_t	0.08	**0.73** *	-0.05	0.14
Ti_t	-0.32	-0.09	-0.28	-0.30
Fe_t	-0.25	-0.20	-0.26	-0.20
Mn_t	**-0.67** *	-0.26	-0.56	-0.52
Cr_t	0.02	0.00	-0.12	0.12
Cu_t	0.07	0.13	0.02	0.05
Ni_t	**-0.66** *	-0.47	-0.50	-0.27
Zn_t	0.08	0.12	0.14	-0.02
Pb_t	-0.30	-0.08	-0.34	-0.19
Ba_t	-0.39	-0.39	-0.21	-0.28
Sr_t	**-0.72** *	-0.28	**-0.72** *	-0.42
Zr_t	-0.03	0.17	0.02	-0.19

Tab. B.12: Correlation coefficients between soil properties and PGM-height for weighted means over 0-10 cm (wm) and the individual topsoil layers (r $>$ 0.4 highlighted).

C Raw Data

Raw Data are available as attached files ”Profile_Data.pdf” and ”Layer_Data.pdf”.