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Holocene environmental change in the Otjiwarongo thornbush savanna (Northern Namibia): evidence from soils and sediments

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Abstract

In the Otjiwarongo region (Northern Namibia), Vertisol–Kastanozem–Calcisol soil associations occur as patches of several hundred hectares in extent. They have formed in fine-grained Mid-Holocene sediments which accumulated on both sides of the subcontinental watershed between the Ugab River draining into the South Atlantic and the Omatako Omuramba draining into the Kalahari Basin. Kastanozem formation cannot be explained by the environments that exist at present. The humification suggests open savanna environments in the past and does not accord with the shrublands and thornbush savanna at present. Using AMS ^{14}C and OSL data, it is possible to distinguish two periods of soil degradation during the recent past. Initially, most of the Kastanozems and Vertisols were buried by slope wash sediments to a depth of several decimetres. This process started in the mid-19th century at the latest. In a second phase, the soils were affected by rill and gully erosion, indicating increased runoff. This occurred during the last decades of the 19th and the first decades of the 20th century, probably as a result of intensified cattle farming. In contrast to other parts of Namibia, the prominent river channels of the Otjiwarongo region, most of them up to 20 m wide and 3–4 m deep, are a result of recent erosion. Degradation of vegetation and soils, and river channel formation, seem to be the main causes of farmland aridification. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Kastanozems; Namibia; Soil erosion; Environmental change; Holocene

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1. Introduction

Degradation and desertification (man-made aridification) of drylands are global phenomena. More than 30% of the land surface on earth is affected by desertification (Hellden, 1991), and much scientific work has been done on the processes and their environmental effects (Mensching, 1990; Thomas and Middleton, 1994; Millington and Pye, 1994). In southern Africa, the drylands of Namibia and the Republic of South Africa are most affected by this process (UNEP, 1992). Since the beginning of the 20th century, white settlers have recorded increasing aridification in Namibia. This seems to reflect grazing-induced vegetation types, which frequently indicate drier conditions than those recorded by meteorologists (Acocks, 1975; Skarpe, 1986). The evidence for climatic or anthropogenic causes of landscape degradation is based on detailed sedimentological, palynological, pedological, geomorphological and ecological studies (e.g. Vogel, 1983; Sugden and Meadows, 1989; Sugden, 1989). Environmental studies in the Karroo show that in the Late Holocene the first degradation of the natural vegetation was initiated in pre-colonial times by hunting and gathering Khoi San and Khoi Khoi herders (Meadows et al., 1994). Signs of recent environmental change exist in Namibia as well (e.g. Walter, 1954a; Seely and Jacobson, 1994; Maurer, 1995; Sander et al., 1998). There does not appear to have been a significant change in precipitation over the period of rainfall record since the 19th century. Walter (1940, 1954a) suggested that landscape aridification in Namibia is primarily an anthropogenic effect on savanna ecosystems induced by intensified cattle farming. The environmental change is characterized by the transformation of open savanna grasslands to shrublands (Kempf, 1994) caused by heavy stocking with cattle or increasing human population pressure (Sander et al., 1998) and concomitant accelerated erosion (Brunotte and Sander, 2000).

A striking pedological feature of the Otjiwarongo region in northern Namibia is the presence of patches of dark, humic soils termed “greyish, earthy soils” (Ganssen, 1960, p. 127). They include Calcisols with thick Ah-horizons, Vertisols and Kastanozems (Eitel and Eberle, 2001) as described in the World Reference Base (WRB) soil classification system (Deckers et al., 1998). The humic horizons are up to 1 m thick. This extent of humification is not possible in the present thornbush savanna because thornbushes cannot supply sufficient organic matter. The formation of the thick Ah horizons is related to an open savanna with a continuous grass cover and a dense rhizosphere.

At present, most of the soils in the Otjiwarongo region are affected by accelerated erosion. Using pedological, geomorphological and modern dating methods, we attempt to clarify how and when the transformation of the savanna grassland environment in the central parts of northern Namibia occurred.

2. Geological, geomorphological and climatic setting of the Otjiwarongo region

The Otjiwarongo region (Fig. 1) is about 250 km north of Windhoek, the capital of Namibia. It is part of the western margin of the Kalahari. During the summer months (September–April), there is 350–450 mm rainfall, which is very variable in space and

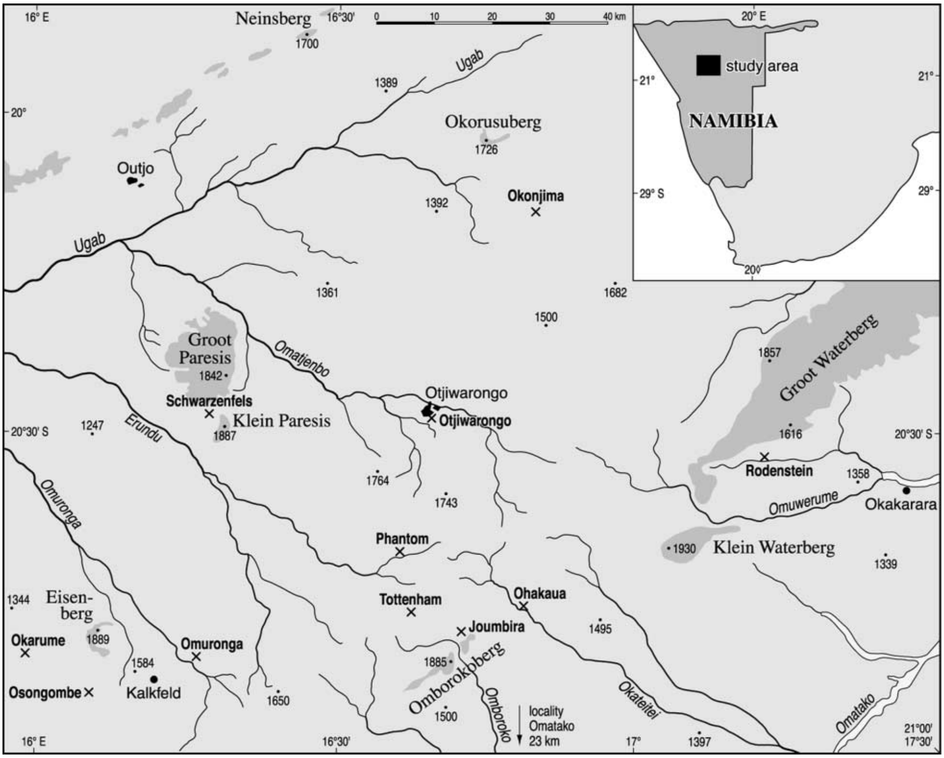

Fig. 1. Map of the study area of the Otjiwarongo region. The crosses indicate localities of typical soil profiles which were analysed.

time. As indicated in the National Atlas of South West Africa (Namibia) (Van Der Merwe, 1983), the potential natural vegetation is an open thornbush savanna with transitions to a more humid, but seasonally dry savanna, in which the trees are larger. Extensive cattle farming is the dominant land use.

The study area is on the flexural bulge which forms the western rim of the intracontinental Kalahari Basin. East of Otjiwarongo at an altitude of about 1600 m a.s.l. lies the watershed between the Ugab River, which crosses the coastal Namib Desert and discharges into the Atlantic Ocean, and the Omuramba Omatako, which terminates endoreically in shallow valleys (plural: omurambo) of the Kalahari Basin. Both of these are ephemeral rivers and most of the tributaries around Otjiwarongo are in shallow valleys because of their watershed position.

The Damara Schists (Precambrian to Lowest Palaeozoic basement) occur widely north and west of Otjiwarongo. An extensive planation surface (the African Surface of King, 1967) resulted from Tertiary denudation processes. A Cretaceous granite complex forms the prominent Great Paresis Mountains (Fig. 1). In contrast to the landsurfaces north and west of Otjiwarongo, widespread Palaeozoic Damara Granite intrusions form an inselberg relief to the south. Mesozoic sedimentary rocks (mainly sandstones, siltstones and

Table 1

Compiled analytical data for typical ‘dark’ soils in the area: (A) Calcisols, Regosol, Arenosol; (B) Kastanozems; (C) Vertisols. For discussion and interpretation see text. For heavy minerals: zrt = content of zircon, rutile and tourmaline (stable fraction), ga = garnet, hbl = hornblende group minerals, sph = sphene, st = staurolite, di = kyanite

(A)

Omatako—Haplic Calcisol

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	> 2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/100 g)	Fe_d (mg/100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
10	Ah1	10YR3/3	15.9	12.6	71.5	0.1	0.2	7.6	0.34	20	158	+	–	–	+++	50	10	11	1		17	11
30	Ah2	10YR3/3	24.0	7.2	68.8	0.1	0.3	7.9	0.33	21	175	+	–	–	+++	55	10	6	1	1	22	5
42	Ahk	10YR4/3	24.6	7.0	68.4	0.1	1.4	7.9	0.33	20	155	+	–	–	+++	61	9	13			13	4
55	2Chkc	10YR5/3	28.3	8.5	63.2	51.2	16.8	8.1		16	100	+	–	++	+++	57	7	9			19	8
75	2Ckc	10YR6/6				15.6	39.2	8.2		7	9											
>110	2Ckm	10YR8/2				3.2	66.8	8.5		4	1											

Okonjima—Petric Calcisol

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/100 g)	Fe_d (mg/100 g)	Clay mineral composition				Heavy mineral composition (%)							
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	st	disth	others
30	Ah1	10YR3/2	10.3	7.8	81.9	0.4	0.3	7.9	0.50	14	234	++++	+	+	–	36	12	22	8	1	8	10	2
40	Ah2	10YR3/2	10.6	7.3	82.1	0.4	0.9	7.8	0.42	13	230	+++	+	+++	–	29	21	19	3	1	7	10	10
50	AhCk	10YR3/3	11.2	6.5	82.3	1.3	5.6	7.9	0.35	13	196	+++	+	+++	–	29	17	23	3		4	12	12
80	Ckc	10YR4/3	10.5	6.5	83.0	5.0	12.6	8.1		9	181	+++	+	+++	–	35	14	18		2	9	16	6
>100	Ckm																						

Otjiwarongo—Petric Calcisol

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/100 g)	Fe_d (mg/100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
40	Ahk	7.5YR3/3	11.7	9.2	79.1	4.7	2.0	7.8	0.47	15	321	++	+	+++	–	12	2	5	73	3	2	4
50	Ahkc	7.5YR3/3	13.4	8.9	77.7	15.8	6.0	7.9	0.48	18	313	++	+	+++	–	14	6	5	71	3		1
70	2Ckc	7.5YR4/4	12.1	8.5	79.4	81.1	11.4	7.8		19	300	++	+	++	–	17	6	3	60	1	5	8
90	2Ckm1																					
>140	2Ckm2	7.5YR4/6	17.9	11.8	70.3	70.8	25.1	7.8		14	304	+	+	++++	–	11	2	3	72	1	2	9

Ohakaua—Eutric Regosol

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/ 100 g)	Fe_d (mg/ 100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
25	Ah1	10YR3/2	25.6	14.5	59.9	1.4	0.1	7.3	0.40	35	512	++	++	+++	–	20	55	6	10	2		7
40	Ah2	10YR3/2	32.9	17.3	49.8	0.9	0.1	7.5	0.44	45	622	++	++	+++	–	22	47	11	15	2	2	1
90	2Ahb	10YR3/3	22.2	14.4	63.5	4.9	0.4	7.7	0.27	28	411	++	++	+++	–	13	58	4	16	2	2	5
>120	3Cw	10YR3/6	17.8	7.2	75.0	19.5	0.3	7.7		30	415	++	++	+++	–	18	59	3	11	2	3	4

Rodenstein—Haplic Arenosol covered by a thin sandy layer

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/ 100 g)	Fe_d (mg/ 100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
18	A/hCw	10YR4/4	9.7	6.1	84.2	0.1	0.2	7.1	0.18	20	168	+++	+++	–	–	75	6	4	3		6	6
25	2Ahb1	10YR4/4	13.4	11.3	75.3	0.2	0.2	6.0	0.24	39	224	+++	+++	–	–	69	5	6	2		8	10
55	Ahb2	10YR3/4	11.8	9.0	79.2	0.9	0.2	6.4	0.29	45	239	+++	+++	–	–	70	4	4	3		10	9
>110	3Cw	10YR4/4	17.4	9.3	73.3	1.2	0.2	4.9		48	293	+++	+++	–	–	68	9	3	2		9	9

(B)

Omuronga—Vertic Kastanozem

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/ 100 g)	Fe_d (mg/ 100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
5	Ah1	10YR3/2	31.8	17.2	50.9	1.8	1.3	7.8	1.27	47	930	++++	+	+	–	16	32	8	29	8	2	5
45	Ah2	10YR3/2	31.2	14.1	54.7	0.9	2.1	7.7	1.04	38	747	++++	–	+	–	22	30	3	19	3	5	18
75	AhCk	10YR3/3	25.6	9.8	64.6	2.5	8.3	7.8	0.48	28	442	++++	–	+	–	15	27	12	30	5		11
>100	Ckc	10YR4/3	25.8	10.2	64.0	4.4	13.0	7.8		22	393	++++	+	+	–	10	32	9	31	3		15

(continued on next page)

Table 1 (*continued*)

Schwarzenfels—Vertic Kastanozem

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/100 g)	Fe_d (mg/100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
35	Ah	7.5YR3/3	37.0	10.7	52.3	0.9	0.2	6.35	0.78	51	1144	++++	+	+	–	40	30	8	13			9
65	AhBw	7.5YR3/3	36.9	9.5	53.6	1.6	0.2	6.4	0.62	50	1175	+++	+	+++	–	36	35	11	10		2	5
100	BCw	7.5YR3/3	33.4	9.1	57.5	2.1	0.1	6.75	0.42	42	1043	++	+	++	–	39	25	15	8	1	4	8
>120	2Ckm																					

Okarumue—Calci-Vertic Kastanozem

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/100 g)	Fe_d (mg/100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
10	Ahk1	2.5Y3/2	39.5	19.4	41.1	0.5	14.9	7.8	1.53	34	430	++++	+	–	–	30	12	10	22	11	2	13
45	Ahk2	10YR3/2	44.3	19.9	35.8	0.7	15.7	7.9	1.10	33	429	++++	+	–	–	31	7	7	31	9		15
100	AhCkc	10YR4/2	34.2	29.4	36.4	1.3	20.7	8.0	0.42	24	349											

Joumbira—Eutric Regosol above Vertic Kastanozem

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/100 g)	Fe_d (mg/100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
10	Ah	10YR2/2	26.1	12.0	61.9	1.8	0.3	7.5	0.86	49	826	++++	+	+	–	43	32	5	4	1	11	4
40	2Ahb1	10YR2/2	38.5	12.7	48.8	0.5	0.2	7.3	1.16	82	1022	++++	+	+	–	31	45	5	3		11	5
55	2Ahb2	7.5YR2/2	45.5	13.2	41.3	0.7	0.2	6.5	0.91	97	1135	++++	+	+	–	44	39	5	2	1	8	1
>80	Cw	7.5YR3/3	34.4	10.7	54.9	1.9	0.2	6.4		71	970	++++	+	+	–	46	32	4	2	1	9	6

(C)

Tottenham—Haplic Vertisol covered by a thin soil-sedimentary layer

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/ 100 g)	Fe_d (mg/ 100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
10	Ah1	10YR2/2	26.7	11.4	61.9	4.5	0.2	6.0	0.80	86	853	++++	+	+++	–	27	33	11	10		7	12
90	Ah2	10YR2/2	38.4	13.3	48.3	2.0	0.2	6.1	0.89	144	1207	+++	+	++++	–	26	29	15	10	2	10	8
120	AhCw	10YR3/2	40.4	12.2	47.4	4.0	0.2	7.3	0.61	71	1238	++	+	++++	–	21	45	10	12	3	1	8
>140	2Cw	7.5YR3/4	29.9	5.2	64.9	23.0	0.2	7.0		55	1218	+++	+	+++	–	24	38	9	14	1	4	10

Osongombo—Haplic Regosol above Haplic Vertisol

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/ 100 g)	Fe_d (mg/ 100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
10	Ah	7.5YR3/3	14.8	13.3	71.9	1.9	1.0	7.8	0.59	31	615	++++	+	+	–	16	32	7	21	8	2	14
45	Cw	7.5YR3/3	10.5	8.0	81.5	18.6	1.4	7.8	0.33	20	441	++++	+	+	–	20	27	11	20	3	3	13
120	2Ahb1	10YR3/2	40.4	13.3	46.3	2.7	1.2	7.8	0.51	73	1038	+++	+	+++	–	21	36	4	19	4	3	12
>140	2Ahb2	10YR2/2	37.2	12.8	50.0	2.5	1.1	7.8	0.41	72	971	+++	+	+++	–	22	41	5	10	3	3	16

Phantom—Haplic Regosol above Haplic Vertisol

Depth (cm)	Horizon	Colour	Clay (%)	Silt (%)	Sand (%)	>2 mm (%)	$CaCO_3$ (%)	pH	SOC (%)	Fe_o (mg/ 100 g)	Fe_d (mg/ 100 g)	Clay mineral composition				Heavy mineral composition (%)						
												illite	kaolinite	smectite	palygorskite	zrt	ga	ep	hbl	sph	micas	others
30	Ah/Cw	10YR3/2	23.8	13.6	62.6	0.5	0.2	5.9	0.53	107	719	++++	+	+	–	24	24	3	35	4	4	5
75	2Ahb1	10YR2/2	39.8	26.3	33.9	0.1	0.2	5.7	1.17	279	1228	+++	+	+++	–	23	20	7	37	2	6	5
130	2Ahb2	10YR3/2	31.3	15.3	53.4	0.1	0.2	5.8	0.45	138	837	+++	+	+++	–	25	16	9	35	2	5	8
>170	2Cw	10YR3/2	33.8	16.6	49.6	0.2	0.2	5.8		114	846	+++	+	+++	–	24	21	5	38	2	4	6

mudstones of the Karoo Sequence) cross the area from northeast to southwest, forming cuestas that resulted from the Waterberg–Omboroko–Etjo lineament, which is at least partly a graben (Eitel, 1996).

3. Methods

The dark soils and sediments typical of the Otjiwarongo region were sampled at 12 sites (Fig. 1) from river bank and roadworks exposures. Soil colour was determined by comparison with the Munsell Soil Color Chart, carbonate content using a Scheibler apparatus, pH ($CaCl_2$) by glass electrode, soil organic carbon (SOC) by oxidation (SOC × 1.72 = soil organic matter, SOM; Kretschmar, 1996) and pedogenic iron oxides by double oxalate extraction (Fe_o, Schwertmann, 1964) and double citrate-dithionite extraction (Fe_d, Holmgren, 1967). Particle size distribution was determined after treatment with H_2O_2 and HCl, sieving and separation of the silt and clay fractions using the Köhn/Köttgen method (Kretschmar, 1996). Heavy minerals were separated using an 80% solution of sodium polytungstate (density 2.8) and identified using a petrographic microscope (Boenigk, 1983). Clay fractions were separated by sedimentation in water. Oriented aggregates that were air-dried, glycollated or heated to 550 °C, were analysed by X-ray diffraction (Velde, 1995). The analytical results were used to classify the soils by the FAO/WRB system (Deckers et al., 1998).

At four representative localities, the luminescence ages of the soil parent materials and sediments burying soils were determined using optically stimulated luminescence (OSL). The OSL ages were obtained from the coarse grain quartz fraction's ultraviolet luminescence emission. To obtain the grain size fractions of a given size range and mineral composition, physical and chemical mineral separation techniques were used (Lang et al., 1996). For sample HDS794, the grain size range was 90–160 μm, for HDS795 it was 160–200 μm, and for HDS796 and HDS797 it was 90–200 μm. The basic age equation is given by

$$\text{Age} = \frac{\text{Palaeodose}}{\text{Dose} - \text{rate}}.$$

(for details, see Wagner, 1998)

To determine the equivalent dose D_E (i.e. the artificial energy dose that produces a luminescence signal equivalent to that of the natural palaeodose), the multiple aliquot additive dose method was used. Artificial irradiation was applied at room temperature using $^{90}Sr/^{90}Y$ beta sources. The OSL shinedown curves were measured at 125 °C using the blue LED stimulation facility of a Risø-Reader TL-DA15 (Bøtter-Jensen et al., 1999). The spectral detection window between 300 and 390 nm was limited by 7.5 mm-thick optical filters (U-340). For assessment of the dose-rate, beta-counting and low level gamma-spectrometry were used to determine the U, Th and K contents. The dose conversion factors given by Adamiec and Aitken (1998) were applied.

^{14}C ages were determined by accelerator mass spectrometry (AMS). The $\delta^{13}C$ values of soil organic carbon and charcoal (mainly from trees) provided environmental interpretation (O'Leary, 1981).

4. Results

4.1. Soil classification and genesis

Analytical data for typical dark soils in the study area are presented in Table 1A–C. Most of the dark soils with thick, humic epipedons can be classified as Calcisols, Kastanozems or Vertisols. Regosols and Arenosols with thick dark topsoils are rare.

Carbonate is present in most parent materials and soils of the Otjiwarongo region. It occurs as an intercalated component in the Damara Schists, as secondary carbonate in Tertiary and Quaternary calcretes and in aeolian dust blown from Kalahari calcrete surfaces and pans into the study area (Eitel, 1994). As shown by Netterberg (1969) and Blümel (1982), descending solutions move the lime to lower horizons where it recrystallizes, forming diffuse secondary carbonate powder, calcareous nodules or petrocalcic horizons (calcretes). In the Otjiwarongo thornbush savanna, Haplic and Petric Calcisols occur (Table 1A), with dark brown to very dark brown Ah horizons up to 50 cm thick but with $<0.6\%$ SOC (ochric horizon). The thick Ah horizons can lead to confusion with Kastanozems in the absence of analytical data.

The Kastanozems in the Otjiwarongo region (Eitel and Eberle, 2001) are characterized by medium to large amounts of secondary carbonate (Calcic Kastanozems), by large amounts of clay (Vertic Kastanozems) or by both (Calci-Vertic Kastanozems) (Table 1B). Most of the diagnostic Ah horizons are 40–60 cm thick and have 1–3% SOM. The large quantities of clay in the Kastanozems can make them very difficult to distinguish from Vertisols. However, X-ray diffraction analysis of the clay fractions showed that the Kastanozems—even with more than 40% clay—contain little or no smectite, whereas smectite is predominant in the Vertisols. In the Kastanozems, illite is the predominant clay mineral, derived mainly from mica in the Damara Schists. Illites do not swell and shrink as

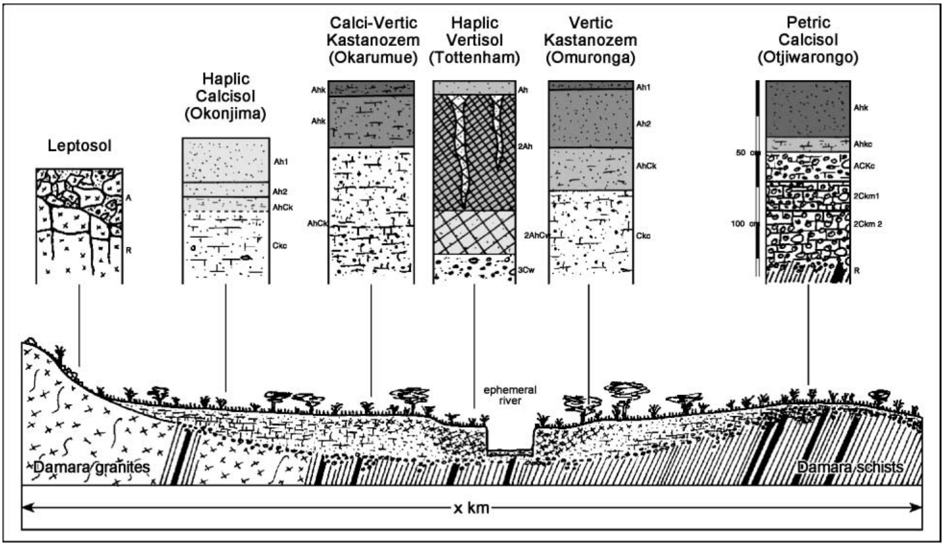

Fig. 2. Schematic soil toposequence in the Otjiwarongo area.

Table 2
$\delta^{13}C$ values, AMS ^{14}C ages [year BP] and OSL ages [ka] for samples from the Otjiwarongo region, northern Namibia

Locality	Analysed fraction	UtC no.	$\delta^{13}C$ [‰]	^{14}C age [year BP]	OSL age [ka]
Omatako (Haplic Calcisol)	Org. C-residue (epipedon)	8898	– 13.8	937 ± 33	6.2 ± 0.6 (host sediment)
Otjiwarongo (Petric Calcisol)	Org. C-residue (epipedon)	8901	– 16.1	7 ± 39	2.1 ± 0.4 ka (host sediment)
Okonjima (Haplic Calcisol)	Org. C-residue Charcoal (epipedon)	8909	– 17.6	391 ± 30	
		8910	– 24.9	517 ± 35	
Ohakaua (Eutric Regosol)	Org. C-residue (epipedon)	8899	– 16.9	1074 ± 41	
Rodenstein (Haplic Arenosol)	Org. C-residue (buried epipedon)	8900	– 13.7	285 ± 30	
Omuronga (Vertic Kastanozem)	Org. C-residue (epipedon)	8905	– 15.9	207 ± 31	
Okarumue (Calci-Vertic Kastanozem)	Org. C-residue (epipedon)	8906	– 20.6	499 ± 36	2.8 ± 0.4 (host sediment)
Schwarzenfels (Vertic Kastanozem)	Org. C-residue (epipedon)	8908	– 14.9	796 ± 29	
Joumbira (Vertic Kastanozem)	Org. C-residue (buried epipedon)	8911	– 14.4	126 ± 29	
Phantom (Haplic Vertisol)	Org. C-residue Charcoal (buried epipedon)	8902	– 17.4	– 50 ± 26	
		8903	– 24.4	112 ± 26	
Tottenham (Haplic Vertisol)	Org. C-residue (buried epipedon)	8904	– 14.0	484 ± 37	
Osongombo (Haplic Vertisol)	Org. C-residue (buried epipedon)	8907	– 15.5	1079 ± 32	0.140 ± 0.02 (cover bed)

smectites do in Vertisols, especially in alkaline soils, so the Vertic Kastanozems do not show deep cracks or slickensides.

The Vertisols in the study area have 0.5–1.2% SOC (Table 1C). Smectites predominate in the clay fraction and were probably formed by cation supply during the rainy season (Milne, 1935). Magnesium availability is a particularly important factor, being derived from magnesian calcite or dolomite in the mica schists (Porada, 1973; Schneider, 1983; Eitel, 1994). However, some of the smectites could be allochthonous since they are known to be transported into valleys and basins of semiarid to semihumid regions (Eswaran et al., 1988; Ahmad, 1996). In the Otjiwarongo region, allochthonous aeolian palygorskite is a third possible source of smectite. This mineral is structurally and chemically similar to smectite (Velde, 1995). It is common in the clay fraction of Tertiary calcretes and calcareous sediments some 10 km north and east of the study area and in the western Kalahari (Watts, 1980; Eitel, 2000), which is a major dust source in southwestern Africa (Eitel et al., 2001).

4.2. Idealized soil toposequence

The watershed between the Ugab and the Omatako catchments is drained by sluggish ephemeral rivers. In the northern and western parts of the study area, the low interfluves mostly result from resistant quartz veins intercalated within the schists. On the quartz vein outcrops rounded quartz pebbles and boulders are widespread. Sometimes they are buried by fine-grained, silty to sandy sediments, which must be of aeolian origin because they cover the elevated sites. South of Otjiwarongo, granitic inselbergs predominate, being covered to a greater or lesser extent by blocky weathering detritus. In such areas, soil toposequences extend over larger areas than in more eroded regions. The almost flat valleys can reach several kilometres in width. Nevertheless, there is systematic variation in their soil cover. A schematic cross-section through an idealized wide, shallow valley in the Otjiwarongo thornbush savanna (Fig. 2) shows granite outcrops associated with Leptosols, whereas the flat landscape on Damara Schists with intercalated quartz veins is associated with Calcisols on elevated sites and Kastanozems and Vertisols in lower parts of the landscape. Downslope, the Calcisol epipedons become more and more humic, changing to Calcic Kastanozems. Below the mollic Ah horizon at 0.5–1.5 m depth these soils often have calcified layers. They merge into Calci-Vertic and Vertic Kastanozems with increasing amounts of clay. Finally, increasing

Table 3
OSL data for samples from the Ojiwarongo region, northern Namibia

	U [$\mu g\ g^{-1}$]	Th [$\mu g\ g^{-1}$]	K [%]	Equivalent dose D_E [Gy]	Total dose-rate [mGy year^{-1}]	OSL age [ka]
HDS 794	1.73 ± 0.05	9.01 ± 0.13	1.26 ± 0.03	15.10 ± 1.34	2.450 ± 0.083	6.2 ± 0.6
HDS 795	2.88 ± 0.10	19.52 ± 0.35	2.15 ± 0.10	8.99 ± 1.52	4.291 ± 0.303	2.1 ± 0.4
HDS 796	3.69 ± 0.09	18.06 ± 0.27	2.15 ± 0.05	12.22 ± 1.56	4.373 ± 0.273	2.8 ± 0.4
HDS 797	2.10 ± 0.07	28.03 ± 0.34	2.96 ± 0.06	0.74 ± 0.10	5.469 ± 0.430	0.14 ± 0.02

smectite content leads to the presence of Vertisols. Gradual transitions from Kastanozems to Vertisols are common.

4.3. Humification

The dark, almost black colours are the most striking feature of the soils. Generally, the accumulation of SOM in thornbush savanna soils is slight because of low biomass production rates. The bushes, mostly acacias, are characterized by small leaves. Termites assimilate the wood from dead bushes and small trees so that mineralization dominates the organic matter budget. The main source of humus in such soils is grass and its rhizosphere, so large amounts of SOM suggest locations favourable for grasses. Under natural conditions in the Otjiwarongo region grass is encouraged by the mean annual rainfall of 350–450 mm. In the northern thornbush savanna near Otjiwarongo, humification of the SOM is favoured by the long dry season (4–5 months) and the intermittent rainfall which restricts mineralization of humus, even during the humid summer. However, there is enough rain to produce a virtually complete grass cover every year. The thick Ah horizons result from a combination of fine-grained substrata and intensive bioturbation, which are both features of the Otjiwarongo region.

The fine-grained substrate needed for formation of thick Ah horizons is provided by calciclastic weathering (fracturing resulting from dissolution and recrystallization of calcite) of the carbonate-bearing Damara Schists (Eitel and Blümel, 1997). The presence of calciclastic residues and fine-grained materials derived from older, Quaternary and

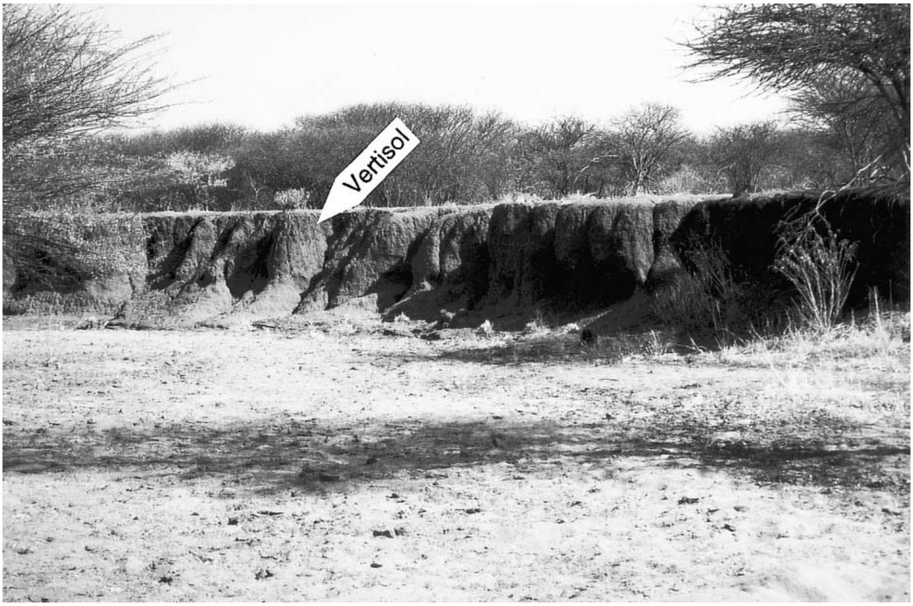

Fig. 3. At Farm Tottenham, an ephemeral river dissects the valley floor and exposes a Vertisol (min. age: 484 ± 37 year BP) formed in more stable environmental conditions in the past. At present, runoff and erosion are intensified (photo, Eitel 08/1998).

Tertiary sediments on the western margin of the Kalahari Basin make large parts of the weakly undulating landsurface ideal for termite activity and burrowing mammals, which mix the SOM with the mineral soil material. The widespread cover-beds on Damara metamorphites explain why most of the Kastanozems are developed outside the granitic inselberg area south of Otjiwarongo.

The high carbonate content of the Damara Schists and the input of calcareous dust results in generally neutral or slightly alkaline soil conditions (pH 7–8). Calcium ions released by dissolution of carbonate in the rainy season stabilize the clay–humus complexes, but in general the precipitation is not sufficient to leach the soils. Together with the intensive bioturbation and the rainfall variability, this prevents mineral transformation and translocation. The lowest pH (pH 5.7) was found in an Ah horizon of a

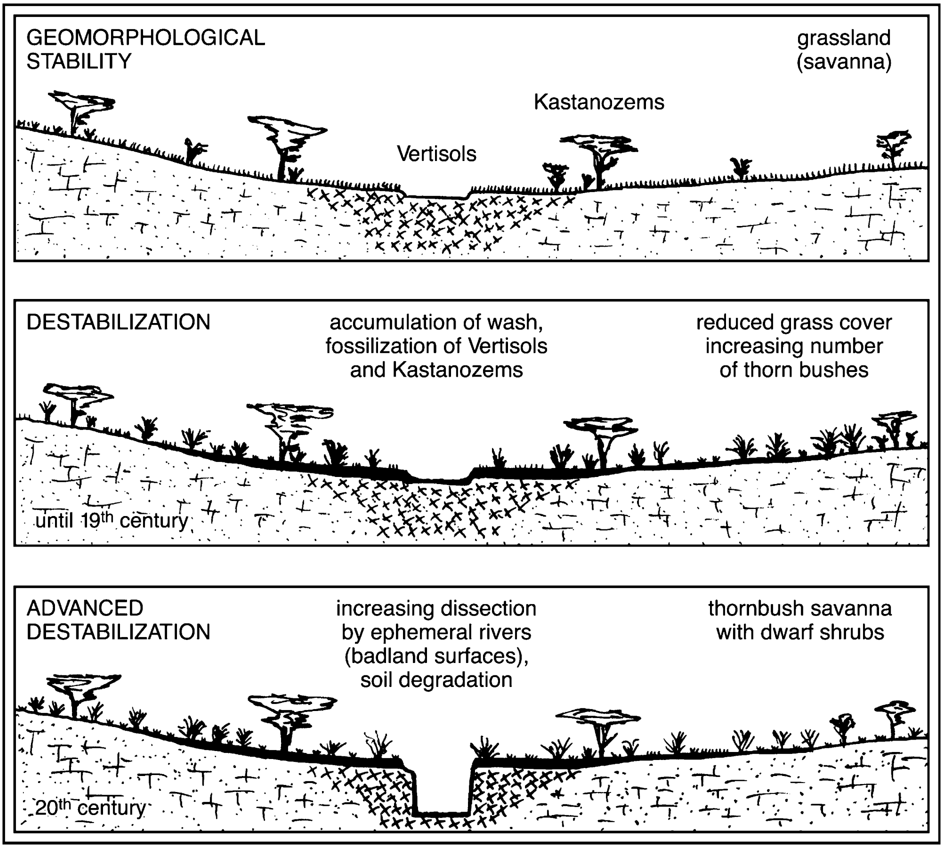

Fig. 4. Sequence of schematic profiles illustrating the degradational phases indicated by soils of the Otjiwarongo region. During a period of geomorphic stability the soil associations formed (above). Early soil degradation is documented by slope wash and accumulations in the basins and shallow valleys, burying the Kastanozems and Vertisols (central profile). At present, ephemeral rivers incise and erode the soils. The processes are linked to a transition from dense grassland to more thorn bushes which indicates primarily human impact (heavy stocking with cattle) (below).

Vertisol on the Phantom Farm (Table 1C). Leaching here seems to result from lateral movement of water in a granitic environment.

^{14}C ages of the SOM range from 1079 ± 32 to 7 ± 39 BP (Table 2) and give minimum ages for humification. δ^{13}C values range from -13.7 to -20.6‰, implying that C4 plants were the main source of the SOM. Only the charcoal has more negative δ^{13}C values (-24.9 and -24.4), and this probably originated from C3 plants such as Acacias.

4.4. Sediments and soil erosion

At three sites (Omatako/HDS794, Otjiwarongo/HDS795 and Okarumue/HDS796), the age of the soil parent materials was determined by OSL (Table 3). The deposits date from the Mid-Holocene (6.2 ± 0.6, 2.1 ± 0.4 and 2.8 ± 0.4 ka). These give maximum ages for soil formation.

At present, most of the soils show features of degradation. The ephemeral rivers dissect the soils on the Mid-Holocene deposits, exposing humic and clay-rich horizons (Fig. 3). Many of the Arenosols, Regosols, Kastanozems and Vertisols are covered before by a less weathered sandy layer resulting from slope wash. The heavy mineral composition at all sites studied confirms that the cover beds and the buried soils are both derived from local sources (Table 1).

The two processes, burial of soils by cover beds and subsequent river incision associated with gully erosion (Fig. 4), were studied in detail in exposures produced by

Fig. 5. At Osongombo-Ost Farm, an ephemeral river dissects the valley floor and exposes a buried Vertisol (min. age: 1079 ± 32 year BP) covered by very young sediments. The maximum age of the channel is indicated by the age of the surface horizon (140 ± 20 years) (photo, Eitel 08/1998).

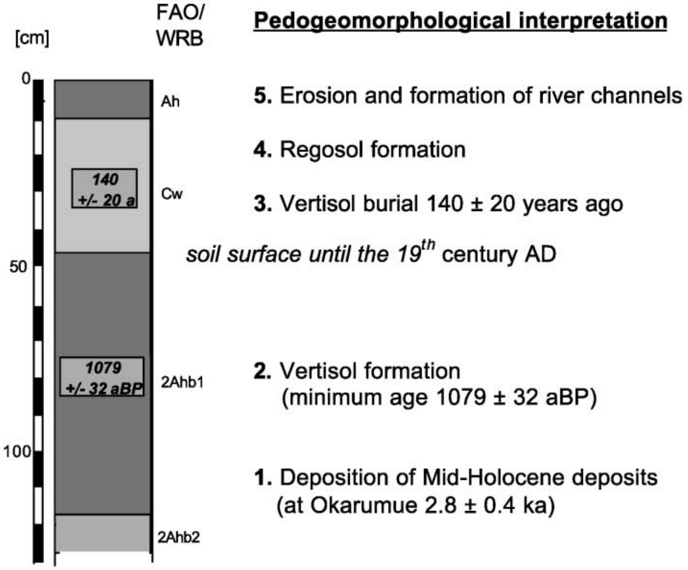

Fig. 6. Sequence of geomorphological and pedological processes indicated in the profile at Osongombo-Ost Farm.

an ephemeral river on the Osongombo-Ost Farm near Kalkfeld (Figs. 1 and 5). The profile (Fig. 6) shows a well-developed Haplic Vertisol in Mid-Holocene deposits. The parent material of the Vertisol belongs to the same stratigraphic unit as that seen some kilometres northwest at Okarumue, where OSL dating gave an age of 2.8 ± 0.4 ka (Table 2). The Vertisol is buried by a sandy layer, which is the parent material of the Haplic Regosols at the surface. The Vertisol indicates stable geomorphic conditions during the Later Holocene. The AMS ^{14}C age of the organic matter in the 2Ahb1 horizon is 1079 ± 32 a BP, which is a minimum age. The overlying sandy cover deposit (thickness 40–60 cm), which is representative for similar cover beds of the Otjiwarongo region, has an OSL (blue) age of 140 ± 20 years (HDS797, Table 3), indicating accumulation in the lowest parts of the valley during the last one to two centuries with subsequent dissection by fluvial erosion.

5. Discussion

The ages of SOC and charcoal indicate that humification of the soils is rather recent, having occurred within the last 1000 years (Table 2). The isotope ratio of the SOC suggests that C4 and not C3 plants (O'Leary, 1981) have contributed most to the soil carbon pool. At present, C3 plants such as acacias are predominant in the Otjiwarongo region and in similar shrublands of South Africa (Stock et al., 1993).

In the Otjiwarongo region, the thick horizons rich in SOM formed under a dense vegetation cover. It is impossible for succulent plants, which show widely varying carbon isotope ratios, to have generated the dark horizons because they are widely spaced and cannot supply enough organic matter for humic epipedons. We suggest that the less negative $\delta^{13}C$ range of the SOM indicates a vegetation cover dominated by C4 plants during the formation of the Vertisol–Kastanozem–Calcisol soil associations (Fig. 7). The C4 plants are more CO_2- and water-efficient than C3 plants, and primarily consist of tropical savanna grasses (Gasse and Lin, 1998) providing a very dense rhizosphere and much organic matter to the soil. A dense grass cover suggests soil formation during a long period of geomorphic stability. Therefore, soil formation under geomorphic stability in the lowest parts of the relief, the presence of thick humic epipedons and the $\delta^{13}C$ values of the soil organic matter all indicate that open grassland existed before processes of environmental change set in to create the present landscape. Open grassland seems to have changed to a thornbush savanna associated with increased hillwash, soil burial, river channel formation and rill erosion. The radiocarbon dates do not indicate very precisely when this environmental change occurred, but suggest a gradually accelerating process of landscape degradation during the last few centuries.

Human impact can explain the environmental change described above. At present in the Otjiwarongo region, the natural vegetation can support only one large animal per 8–10 ha (Van Der Merwe, 1983). Overstocking would have reduced the grass cover, favoured establishment of bushes (Walter, 1954b; Walter and Breckle, 1999) and caused erosion of surface soil horizons. Under intense rainfall, erosion on the upper slopes led to burial of soils on the lower slopes. The erosional processes also caused the plant cover, especially the grasses, to become increasingly diffuse, and led to river incision and gully erosion of the clay-rich Vertisols and Kastanozems.

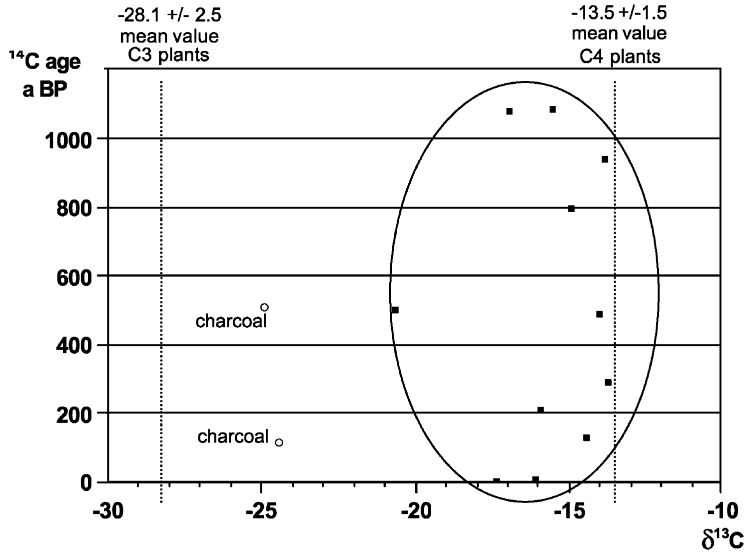

Fig. 7. $\delta^{13}C$ values for soil organic carbon (ringed) and charcoal (from Acaciae?) from 12 Ah horizons (localities in Fig. 1). The less negative $\delta^{13}C$ values suggest mainly C4 plants (grasses) as the source of the humus.

The overgrazing leading to slope wash and soil burial as first steps of landscape alteration probably occurred in the mid-19th century at the latest, perhaps as a result of increasing density of the local Bantu population (Herero). At the end of the 19th century, when European settlement started, ca. 100,000 Herero lived in the northern parts of Namibia (Langhans, 1897), and the Otjiwarongo–Waterberg region was one of the core areas of Herero farming. During the pre-Bantu period, the human impact on the natural environment by hunting and gathering Khoi-San people was probably small, and soil formation, even in the lowest landscape positions, was uninterrupted.

At Osongombo-Ost, the OSL age of the cover bed shows that the subsequent gully erosion and dissection by ephemeral river channels is a very young feature of the region, possibly caused by local cattle farming since the immigration of European settlers. This concurs with the observations by Carl Johan Andersson (1828–1867) and other explorers, who reported before the period of European settlement that game was still abundant on rich grasslands in the Kalahari (Werther, 1935, p. 67). Walter (1954a, pp. 26–27) cites eyewitness accounts that the Erundu River (Fig. 1) did not exist when the farms were surveyed in 1911. In 1950, the Erundu channel was already 3 m deep and more than 40 m broad. This transformation of shallow, low-energy omurambo covered with dense vegetation to incised high-energy river channels transporting sand and even boulders has also been described by Seydel (1943/1951) for the Swakop River and by Mühlenbruch et al. (1942) for the Ugab and Omaruru Rivers.

During the first years of colonization, it is likely that shooting of large browsers, including the almost complete elimination of elephants, favoured the growth of bushes and trees in the farmland. After the Herero war of 1904–1906, the population of German settlers increased from some hundreds in 1896 to 4032 on 1245 farms and in 315 small settlements in 1912, with approximately 13 million ha of farmland (citations in Demhardt, 2000, p. 192). One of the core areas of German settlement was the former Hereroland in the Kalkfeld–Outjo–Otjiwarongo area west of the Waterberg. Heavy stocking with cattle and the use of the omurambo grasslands as roads for oxcarts and horses (Seydel, 1943/1951, p. 23) probably destroyed the dense vegetation cover and made this area susceptible to erosion and gullying.

6. Conclusions

In the Otjiwarongo region, the fine-grained Mid-Holocene sediments and related soils rich in organic matter are an important natural resource. Our work shows that the dark surface soil horizons of Vertisols, Kastanozems and Calcisols were formed under open grasslands in shallow valleys which existed until the 19th century. At present, most of the soils are affected by erosion. Pedological and geomorphic investigations distinguish separate degradational stages in space and time caused by different periods of human impact. Landscape degradation seems to have started in pre-colonial times (Bantu immigration?) most likely as a consequence of cattle farming, and was increased by farming since the end of the 19th century by European settlers. In contrast to former ideas that the incised river channels are a natural feature of the Otjiwarongo region, there is pedological and geomorphic evidence that they result from these recent changes in settlement and land use patterns.

The fertile soils on Mid-Holocene sediments, especially the Kastanozems and the Calcisols with thick Ah horizons, are water retentive and therefore provide good grazing for cattle and game. With erosion and river channel formation, drainage is intensified and subsequent aridification of the farmland sets in, which is probably documented by reduced growth of trees since the end of the 19th century (Huss, 1944). Therefore, aridification is not only a result of grazing-induced vegetation types (Skarpe, 1986), but is also caused by increased runoff, as suggested by Walter (1940). River channel formation and soil loss is not reversible. In areas which have not been greatly affected by erosion, removal of acacia bushes and trees can assist the re-establishment of natural grassland, which would stabilize the soil surface. However, this is costly as it is heavy labour and it would require a reduction of cattle stocks for several years at least.

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