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Anthropogenic erosion-induced small-scale soil heterogeneity in South African rangelands

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ABSTRACT

Land-use-induced soil erosion in semi-arid drylands induced by land-use changes creates patchworks of soils and vegetation different from those of natural conditions. Knowledge of the highly dynamic spatial heterogeneity in soil properties, not depicted in conventional soil maps, is important for managing land uses sustainably, and for understanding soil-climate interactions. This analysis of soil redistribution in a degraded rangeland in South Africa assessed the significance of anthropogenic soil heterogeneity within a small catchment with a silted reservoir. This study carries out analysis of soil redistribution in a degraded rangeland in South Africa, to assess the significance of anthropogenic soil heterogeneity within a small catchment with a silted-up reservoir. Surface soil (N = 51) and soil profile (N = 29) samples were collected from areas of various degrees of degradation and analysed for texture, pH, total nitrogen (TN), total organic carbon (TOC), available phosphorus (P), and potassium (K). Diverse vegetation cover is reflected in a high soil heterogeneity, showing differences in soil texture. Average surface soil nutrient content was significantly higher in vegetated areas (grassland: TOC 1.08 %, TN 0.10 %, P 20.12 mg kg^{-1}, mixed vegetation: TOC 0.93 %, TN 0.08 %, P 13.54 mg kg^{-1}, depositional: TOC 1.68 %, TN 0.18 %, P 34.67 mg kg^{-1}) than at degraded sites (TOC 0.47 %, TN 0.06 %, P 7.52 mg kg^{-1}). K content was low to moderate but did not show any significant difference between landscape units. Potential exists for the formation of distinct young anthropogenic soils on the silted-up reservoir where deposited sediments differed in TOC, TN, P, and profile depth from the shallow natural soils. Consequently, azonal soils on dam-deposits are different from those occurring naturally, and not depicted on conventional soil maps. Their different water and nutrient cycling may affect vegetation and biogeochemical fluxes.

Land-use management should consider such soils, as they play an important role in rangeland ecology.

1. Introduction

Soil erosion plays an important role in the global carbon (C) cycle (Berhe et al., 2005; Harden et al., 1999; Lal, 2005, 2003). However, there is an ongoing debate whether erosion generates a net C source or sink for atmospheric C (Chappell et al., 2016; Lal, 2019; Sanderman and Berhe, 2017; Van Oost et al., 2007). Dryland ecosystems are vulnerable to soil erosion due to unevenly distributed or erratic rainfall and frequent droughts (FAO, 2004). Soil erosion in semi-arid drylands often leads to a redistribution of soil, thus creating a heterogeneous patchworks of soils and, consequently, vegetation, that are different from their natural conditions (Cerdá, 2001; Ludwig et al., 2005; Rietkerk et al., 2002). Different soil characteristics, such as nutrient content (Rietkerk et al., 2002; Schlesinger et al., 1996) or soil erodibility (Cerdá, 1997; Dickie and Parsons, 2012) are associated with patches of bare soil and vegetation. This small-scale spatial heterogeneity in soil parameters is highly dynamic and usually not depicted in conventional soil maps due to scalar impracticalities in their physical demarcation. Apart from impoverishment of soils by erosion, deposition of the eroded material contributes to the patchiness of soils (Bochet et al., 1999; Okin et al., 2006; Puigdefábregas, 2005).

The Karoo rangelands in South Africa are characterised by a wide range of erosion features, including silted-up reservoirs (Boardman, 2014; Boardman et al., 2003), which makes them ideal for studying soil redistribution and soil patchiness. Behind small dams, which were built to retain water or sediments (Boardman et al., 2003; Lü et al., 2012), deposits formed both intentionally and unintentionally when the reservoirs silted-up. In both cases, the sediments form deep bodies of substrate on which young soils are forming. These sediment patches are often high in nutrient concentration and have an increased soil productivity (Haregeweyn et al., 2008). As a consequence, depositional areas behind dams often develop specific vegetation assemblages (Polyakov et al., 2014), which promote

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livestock grazing and thus generates a particular ecological or even economical value. Even though this affects only spatially limited areas, these hotspots of soil productivity p. could be a considerable factor for soil management and rehabilitation in these nutrient poor areas. The lack of spatial information on these human-induced soil patchworks potentially affects the assessment of rangeland soils on global C cycles, as well as their appropriate management (FAO, 2004).

The purpose of this study is to undertake a high-resolution analysis of current soil formation in a small degraded catchment that is considered to be representative for other rangelands. The small-scale variability of the soils is documented in order to assess the relevance of the human-induced soil redistribution for land management, soil restoration and soil-climate interaction. The research questions of the study are to determine (1) how heterogeneous are soils in the studied area?, (2) are they associated with specific landscape units?, (3) to what extent is the spatial heterogeneity of the soils reflected in conventional soil maps?, (4) to what extent can anthropogenic soil erosion accelerate soil

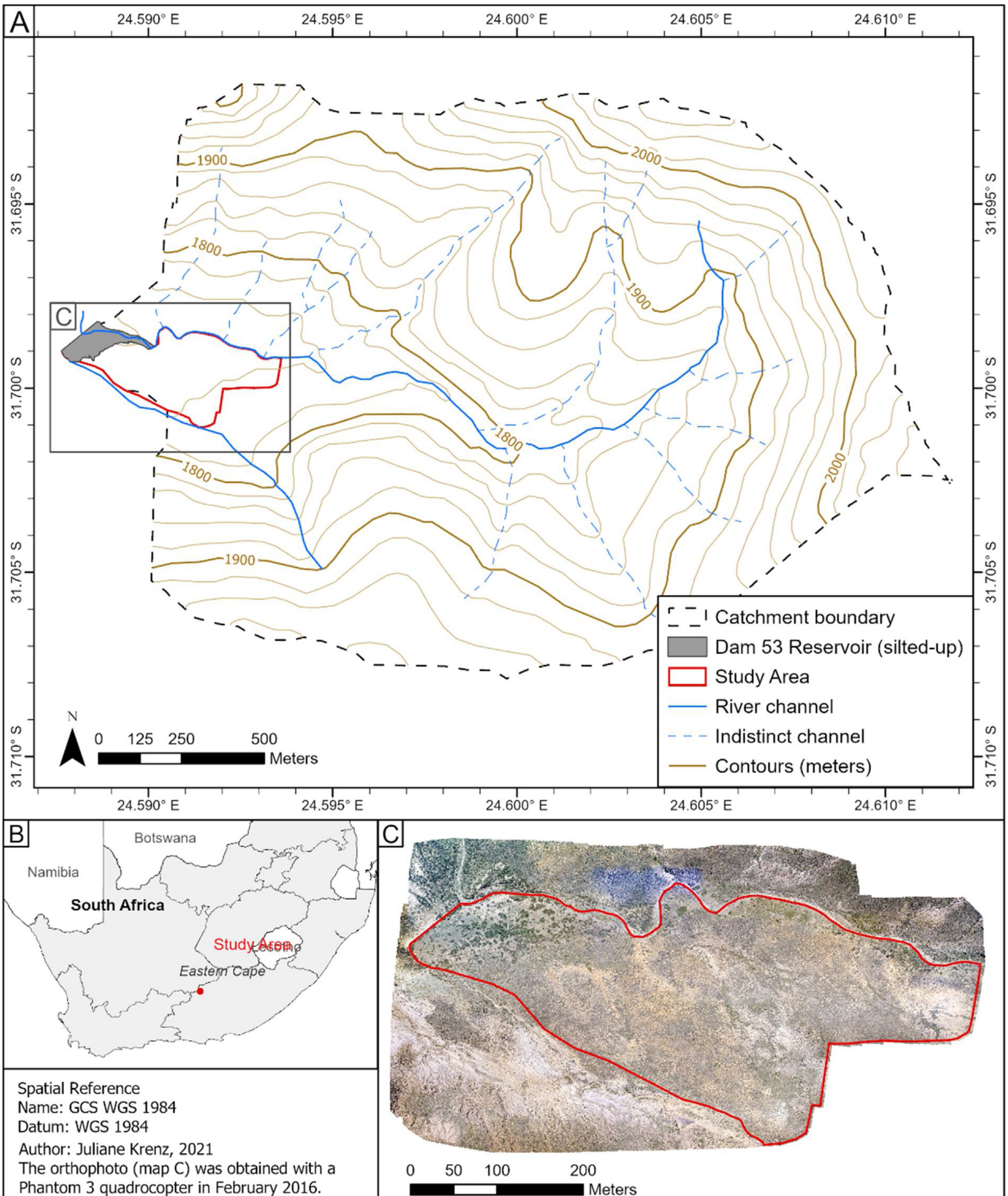

Fig. 1. Overview of the studied catchment area (A) in the Karoo Rangelands of the Eastern Cape, its location within South Africa (B) and an orthophoto (C) from the area. The orthophoto was captured in 2016, as described in Krenz and Kuhn (2018).

formation?, and (5) how could azonal soils be considered in efforts to restore degraded drylands?

2. Study area

The study area (Fig. 1) is located in the Sneeuberg uplands in the Eastern Cape Province of South Africa which rise up to 2502 m at Kompassberg. Geologically, the area is composed of Upper Permian to Triassic mudstones and sandstones from the Beaufort Group, interspersed with Jurassic dolerite sills and dykes that outcrop on hilltops (Catuneanu et al., 2005; Viglietti et al., 2017). With an average annual rainfall (1988–2007) at nearby Compassberg farm of 498 mm (Boardman and Foster, 2008), the region is wetter than the surrounding lowlands due to orographic rainfall (Sugden, 1989), and is characterized by a summer rainfall regime, where approximately 70 % of the annual precipitation is received between October and March (Keay-Bright and Boardman, 2007). Vegetation is classified as False Upper Karoo in the valleys, and Karroid Merxmuellera Mountain veld on the hillslopes (Acocks, 1975). Vegetation consists of a mixture of palatable and unpalatable grasses (e.g. *Merxmuellera disticha),* and shrubs (e.g. *Chrysocoma ciliata*, *Dicerothamnus rhinocerotis*, *Euryops annae,* and *Selago* spp.). Vegetation shows no regular pattern (Krenz et al., 2019) such as spotted, banded, tiger stripes (Rietkerk et al., 2002), or clumped, which is otherwise a common feature in Karoo shrublands (Blignaut and Milton, 2005).

Soils are usually derived from the underlying doleritic material or silt, mud- and claystones (Council for Geoscience, 2008; ISRIC, 2006) and are described as lithic Leptosols (ISRIC, 2006). Wide valleys have often been infilled with colluvial and alluvial material. Soil profiles are mostly shallow and often lack a distinct A horizon, presumably due to high erosion rates (Boardman et al., 2017, 2003). Soil maps of the study area are only available at a national scale and have a resolution of 1:1,000,000 (ISRIC, 2006), 1:2,000,000 (Council for Geoscience, 2008), and 1:5,000,000 (Soils Research Institute, 1965). Thus, spatial information on soils at the scale needed by farmers and land-managers is limited.

Historically, the area was used for sheep and cattle farming since the 18th century, but a permanent farm, Aandrus, was only established in the 1860s or 70 s (Keay-Bright and Boardman, 2007). Grazing densities in the Sneeuberg region were about 10 large stock units (LSU) per km^2 in the beginning of the 20th century (Keay-Bright and Boardman, 2006), but have now been reduced to about one LSU per 18 ha (Jacobs, D., current manager of the farm, personal communication 2016).

The Sneeuberg area shows typical features of land degradation, such as shrub encroachment and soil erosion, including rills, gullies and permanently crusted surfaces. Due to the intense grazing in the valley bottoms, they are most affected by erosion (Boardman et al., 2003; Foster et al., 2007). Another common feature are infilled reservoirs, which are now dry because dams have breached and in many instances are not economical to repair or maintain (Boardman et al., 2003). Boardman and Foster (2011) mapped 106 small farm dams in an area of approx. 100 km^2 in the Sneeuberg region, of which almost 50 % are full of sediment with little or no remaining water storage capacity. Although the dams cover only a limited extent the flat depositional areas (slopes shallower than 5°) between the alternating steep slopes account for roughly 25–40 % of the Sneeuberg region.

The study site was chosen because it was only used for grazing. Unlike other catchments where crop farming, including the construction of terraces ("bunds") has caused more complex patterns of soil redistribution, our study site represents a simple environment from a geomorphological perspective to assess cause and effect of soil erosion on soil properties. A silted-up reservoir (31.698558 °S, 24.588183 °E, Fig. 1), labelled Dam 53 according to the reference system adopted by Boardman and Foster (2011), is located in a small and easily accessible catchment (3.2 km^2) located at an altitude of approximately 1740 m a.s.l. The 140 m long dam wall was probably constructed in the 1930s and anecdotal evidence suggests that it was breached during a prolonged storm in 1974 (Boardman et al., 2017). This allowed for some 40 years of soil development in the former reservoir area after about 60 years of sedimentation. This colluvial depositional area, from immediately behind the dam up to the toe of the surrounding slopes, represents the actual study area and extends to approx. 10.4 ha. The initial reservoir water storage capacity was approximately 30,490 m^3 when constructed and comprised an area of roughly 1.2 ha. Since the breach, an ephemeral stream has incised more than 5 m into the dam deposits and to date has re-excavated approximately 2900 m^3 of dam-derived sediment (Krenz and Kuhn, 2018). The latest assessment of soil degradation, based on high-resolution UAV imagery (Krenz et al., 2019), showed that an area of approximately 23–29% of the land within Dam 53 catchment as being seriously affected by water erosion.

3. Material and methods

3.1. Soil sampling

Soil samples were collected throughout the study site, from areas of various degrees of soil and vegetation degradation, to identify differences in soil properties. Vegetation was used as an index for soil degradation because in rangelands it often reflects the different chemical, structural and textural soil properties (Schlesinger et al., 1996, 1990). Soil samples assigned to the designated landscape units (LU) are described in Table 1 and illustrated by exemplary photographs in Fig. 2.

In total, 51 surface soil samples (0–5 cm) were collected from depositional (N = 16), degraded (N = 14), grassland (N = 8), and areas of mixed vegetation (N = 13) through scraping off topsoil of a few nearby points in order to average out very localised heterogeneities. The area of the former reservoir (depositional LU) is the preferred grazing spot for browsing and grazing animals. To avoid heterogeneities introduced at the surface, including trampling, burrowing, and droppings, two one-meter deep soil cores were retrieved. In addition, soil pits were dug in the degraded LU (N = 6), grassland LU (N = 8), and mixed vegetation LU (N = 13) to study potential differences in soil depth and the vertical distribution of texture and nutrients. Except for one pit, all soil pits were located in the flatter depositional area of the catchment. Bulk soil samples were taken for each identified soil horizon. At some sampling sites in the degraded LU soil was so compact that it was impossible to take a complete set of surface and profile samples. The distribution of LUs and all sampling locations are mapped in Fig. 3.

Table 1
Characteristics of different landscape units (LUs) for soil sampling. The threshold value of at least 50 % vegetation cover for the vegetated LU was chosen according to the Karoo Veld assessment form in Esler et al. (2006), where an excellent veld condition is characterised among others by > 50 % vegetation cover.

Landscape Unit (LU)	Description
Depositional	Former reservoir area, Flat terrain behind the former dam wall
Degraded	Contiguous area of bare soil with little vegetation (individual shrubs or tussock grass) and large gaps between individual plants, vegetation cover < 50 % Rill development Shrubs or tussocks often stand on pedestals
Grassland	Contiguous vegetation cover (> 50 %), non-woody plants dominating
Mixed Vegetation	Contiguous vegetation cover interspersed with patches of bare soil or stones, at least 50 % vegetation cover, neither woody nor non-woody plants dominating

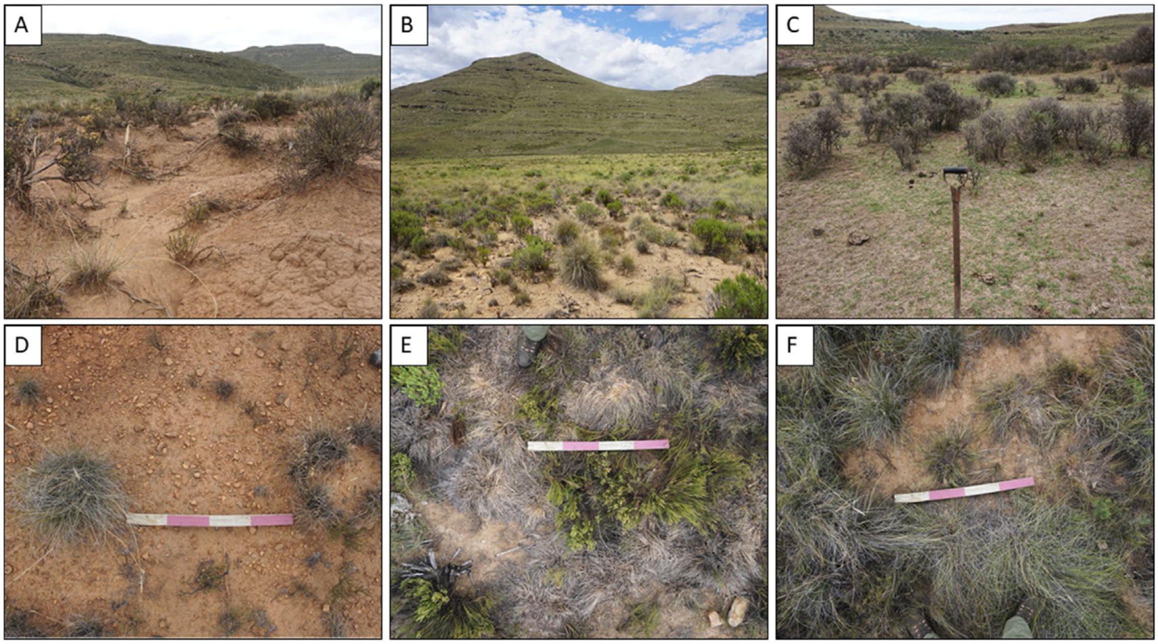

Fig. 2. Impressions from the study site for the different LUs: degraded LU (A, D), mixed vegetation LU (B, E), depositional LU (C) and grassland LU (F). One segment of the scale bar in the bottom row pictures represents 20 cm.

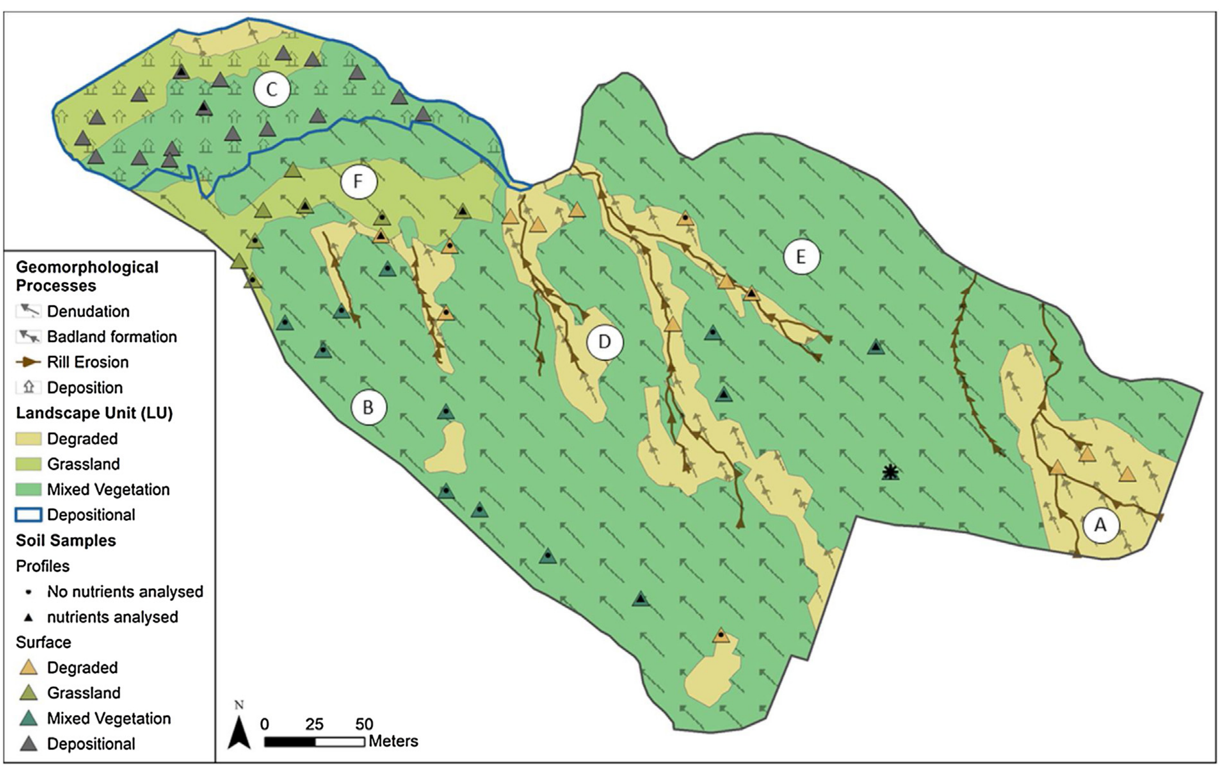

Fig. 3. Map showing landscape units and locations of top soil samples. Samples marked with a dot inside the triangle are locations where soil profile samples were taken as well. The sample marked with a black asterisk was the only one situated at the toe of the slope and had an unusually deep soil profile (modified from Krenz et al. (2019)). The circled letters on the map refer to the approximate locations of field impressions from Fig. 2.

3.2. Laboratory analyses

Texture, pH, total organic carbon (TOC) and nutrients such as total nitrogen (TN) and available phosphorus (P) and potassium (K) content were analysed to characterise soils from the different sampling sites. Variations in these soil properties were interpreted as evidence of differences in soil quality and indicative of soil erosion and depositional processes (Lal et al., 1999). All laboratory analyses were carried out in the soil laboratories within the Department of Environmental Science at the University Basel. Prior to analysis all soil samples were dried at 40 °C and passed through a 2 mm sieve. pH was measured in an aqueous solution with a

SevenExcellence pH-meter (Mettler-Toledo, Columbus, OH, USA). Particle size analysis (PSA) was performed using laser diffraction with three minutes ultrasound energy for more thorough aggregate dispersion (Malvern Mastersizer 2000, Malvern Panalytical, Almelo, The Netherlands). Prior to PSA measurement, organic compounds were removed by heating 1 g of soil mixed with 10 mL of distilled water and 10 mL of 30 % hydrogen peroxide in a water bath.

Both the TOC and TN content are one of the main indicators of soil quality in semi-arid soils (Muñoz-Rojas et al., 2016; Sharma et al., 2005). Total organic and inorganic carbon were analysed from dry sieved samples using a LECO RC 612 Carbon Analyzer at 550 °C (LECO RC 612, LECO Corporation, St Joseph, MI, USA). Total nitrogen (TN) was analysed by dry combustion at 1050 °C (LECO CN628, LECO Corporation, St Joseph, MI, USA).

Due to restricted analysis capacities during the COVID pandemic, only a selection of samples was analysed for potassium (K) (grassland N = 2, mixed vegetation N = 4, degradation N = 2, depositional N = 2) and available phosphorus (P) (grassland N = 5, mixed vegetation N = 8, degradation N = 6, depositional N = 16). Individual element analysis was favoured over cation exchange capacity (CEC), since CEC differs strongly with pH which complicates drawing comparisons between different samples (Chapman, 1965; Sumner and Miller, 1996). Hence, available P and K, as macronutrients for plant growth were expected to adequately encapsulate the soil's nutrient status and capacity for plant development. K was analysed by ICP-OES 5100 Spectrometer (Agilent Technologies, Santa Klara, California, US). P was analysed by Olsen test (Olsen and Sommers, 1982) and UV–vis Spectrophotometer (Lambda 365, PerkinElmer, Waltham, MA, USA).

3.3. Vertical interpolation of soil parameters

Only one soil sample was taken per horizon and analysed in the lab. The irregular depths of soil samples complicate the comparison and grouping of data from several profiles within the same LU. A depth-wise interpolation and visualisation of soil parameters was therefore conducted using the R software package "aqp" (Beaudette et al., 2013). Soil property data from each soil profile were normalised, aligned to a common depth and resampled at a regular depth-interval of 1 cm. Afterwards the soil property was summarised for each LU separately along depth intervals up to the maximum profile depth. The fraction of profiles contributing to the computation of the aggregated value is calculated at 10 cm intervals.

3.4. Statistical analysis

Statistical analyses of soil data focussed on identifying potential differences within LUs and between LUs. Basic statistics included median, first and third quantiles for all soil parameters and all LUs (depositional, degraded, grassland and mixed vegetation) were included. Additionally, non-parametric statistical tests were used to compare datasets from different LUs as normality could not be assumed. Normality of distributions was tested with the Shapiro-Wilk test individually for each variable. However, even for the variables where the null-hypothesis of a normally distributed population was tested positively, we cannot assume normality of our data because of our small sample sizes. We applied a Kruskal-Wallis test for our datasets with four groups (LUs) and a subsequent pairwise comparison in RStudio (Version 1.2.1335), based on R version 3.5.3. using a significance level of 0.05.

4. Results

4.1. Top soil characteristics

Topsoil characteristics and results of the pairwise comparison are shown in Tables 2 and A1, respectively. The major texture class according to the FAO soil classification (FAO, 2006) is sandy loam (32 out of 51 samples); eight samples are classified as loamy sand, six as loam and five as silty loam. All silty loam samples were found in the depositional LU. There was a significant difference in particle

Table 2
Top soil characteristics of landscape units. For available phosphorus (P) and potassium (K) a smaller samples size was analysed (P: depositional N = 16, degradation N = 6, grassland N = 5, mixed vegetation = 8; K: depositional N = 2, degradation N = 2, grassland N = 2, mixed vegetation = 4).

Parameter		Landscape Unit			
		Depositional	Degraded	Grassland	Mixed Vegetation
Area [ha]		0.91	1.63	0.44	5.8
N		16	14	8	13
D10 [μm]	Mean	2.90 ± 0.93	3.84 ± 2.77	4.21 ± 1.74	3.49 ± 1.72
	Minimum	1.49	1.47	2.26	1.80
	Maximum	4.40	10.55	7.28	8.79
D50 [μm]	Mean	51.52 ± 21.59	95.45 ± 48.34	98.20 ± 34.64	84.68 ± 16.33
	Minimum	12.83	26.82	68.56	43.26
	Maximum	90.83	215.15	176.78	109.96
D90 [μm]	Mean	134.92 ± 37.63	407.87 ± 210.27	350.81 ± 184.34	346.97 ± 116.62
	Minimum	66.29	140.18	175.23	219.34
	Maximum	191.97	814.37	746.11	591.60
pH	Mean	5.55 ± 0.35	6.47 ± 0.35	6.11 ± 0.18	6.05 ± 0.28
	Minimum	4.9	5.70	5.87	5.61
	Maximum	6.3	7.12	6.24	6.71
TOC [%]	Mean	1.68 ± 1.13	0.47 ± 0.20	1.08 ± 0.18	0.93 ± 0.21
	Minimum	0.63	0.12	0.85	0.69
	Maximum	4.86	0.78	1.31	1.35
TIC [%]	Mean	0.04 ± 0.02	0.01 ± 0.003	0.02 ± 0.004	0.02 ± 0.003
	Minimum	0.02	0.01	0.02	0.02
	Maximum	0.09	0.02	0.03	0.02
TN [%]	Mean	0.18 ± 0.1	0.06 ± 0.01	0.10 ± 0.03	0.08 ± 0.02
	Minimum	0.09	0.04	0.08	0.05
	Maximum	0.47	0.08	0.16	0.12
P [mg kg^{-1}]	Mean	34.67 ± 14.82	7.52 ± 2.81	20.12 ± 5.31	13.54 ± 3.21
	Minimum	20.30	3.28	12.606	8.20
	Maximum	70.55	12.54	27.484	17.44
K [mg kg^{-1}]	Mean	16.12 ± 1.13	7.13 ± 2.88	19.12 ± 1.88	12.44 ± 3.48

size distributions between the depositional and the other LUs (Fig. 4, Table A1), inasmuch as that average D10, D50 and D90 diameters were finest for the depositional LU. Overall TOC, TIC and TN content were low, P and K low to moderate. At a 95 % confidence level, pH, TOC, TIC, TN and P content of the topsoils showed significant differences between the four LUs. The TOC content is generally low (Table 2) and varies for all top soil samples between 0.12 % and 4.86 %; with a mean of 0.47 % for the degraded, 0.93 % for the mixed vegetation LU, 1.08 % for the grassland LU, and 1.68 for the depositional LU. TIC content was low and showed significant differences for all pairwise comparisons. TN and P was highest for the depositional LU (TN: 0.18 %, P: 34.67 g kg^{-1}) and lowest for the degraded LU (TN: 0.06 %, P: 7.52 g kg^{-1}). Comparing LUs pairwise, there is a significant difference of P and TIC for all LUs (Fig. 4, Table A1). The heterogeneity within the depositional LU was high with regard to TOC, TIC and TN and P, and for the mixed vegetation LU with regards to TN and pH.

4.2. Soil profile properties

Soil profile depth varied between 32–54 cm for the degraded LU, 34–70 cm for the grassland LU, and 39–62 cm for the mixed vegetation LU. One profile from the mixed vegetation LU had a depth of 110 cm. This profile was located in the South East of the catchment and is marked with a black asterisk in Fig. 2. The deep soil depth can probably be attributed to the profiles' location at the toe of a hillslope. For all soil profiles, it should be noted that profiles were not dug down to bedrock, but were restricted by the compacted strata. Hence, it was only possible to sample six soil profiles for the degraded LU compared to 13 profiles for the vegetated LU.

For all profiles, average D10, D50 and D90 sizes declined with increasing depth, with the strongest trend expressed by the degraded and mixed vegetation LU (Fig. 5). The vertical nutrient distribution showed opposite patterns for the LUs. While TOC and TN increased above 12 cm and steadily decreased with depth below approximately 12 cm for the degraded and mixed vegetation LU, both first decreased and then increased for the grassland LU. Both P and K decreased with increasing depth, with the strongest trend expressed in the depositional LU for P and in the grassland LU for K. pH steadily increased from slightly acidic at the upper layer, to slightly alkaline in the deeper soil layers.

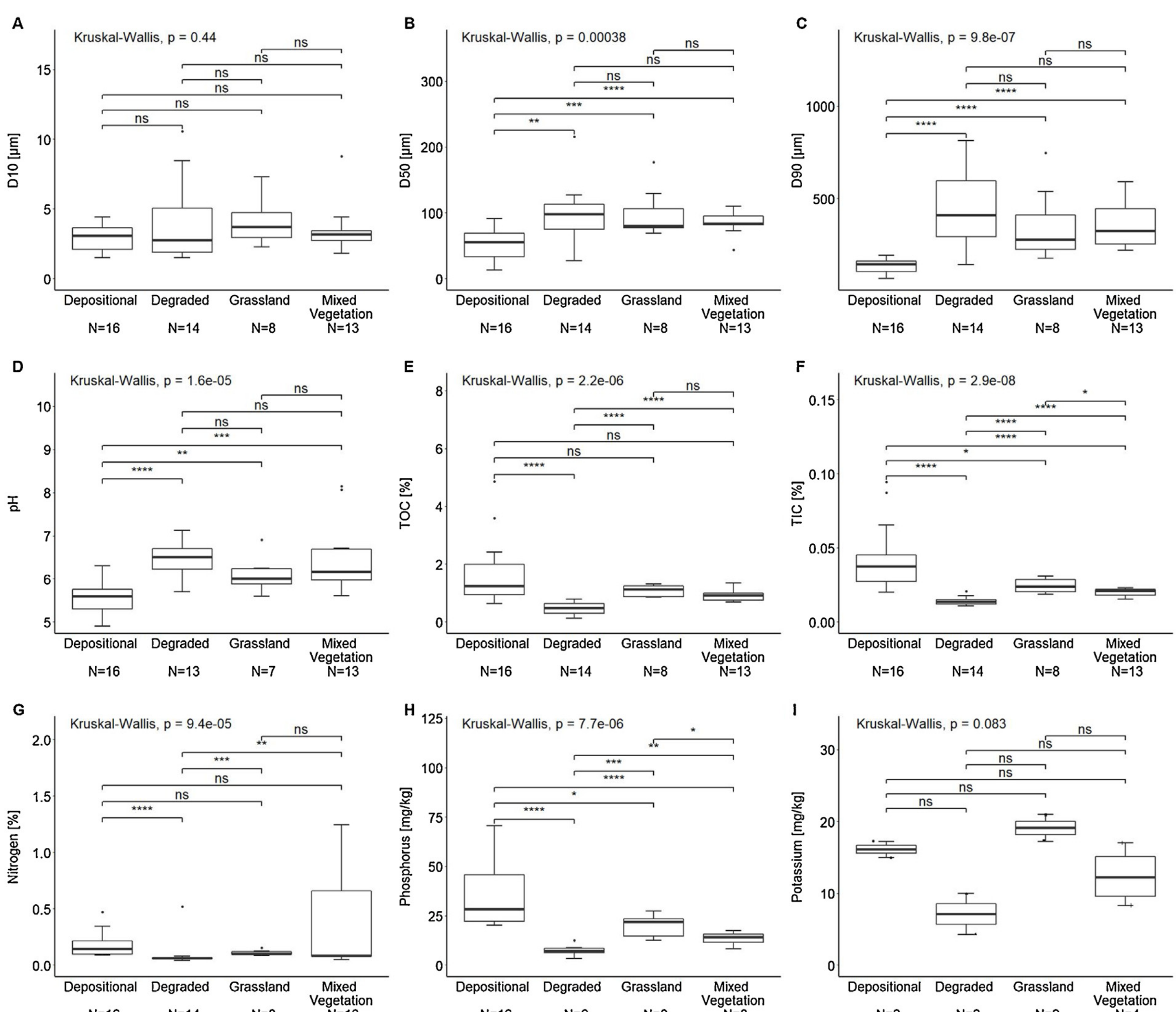

Fig. 4. Pairwise comparison of physical and chemical properties of surface soils. Please note the different axis ranges for each variable and the reduced sample size for pH, Phosphorus and Potassium measurements. Significant differences are represented with *($p \leq 0.5$), ** ($p \leq 0.01$), *** ($p \leq 0.001$) and **** ($p \leq 0.0001$) and ns (no significant). Exact p-values are attached in Appendix A.

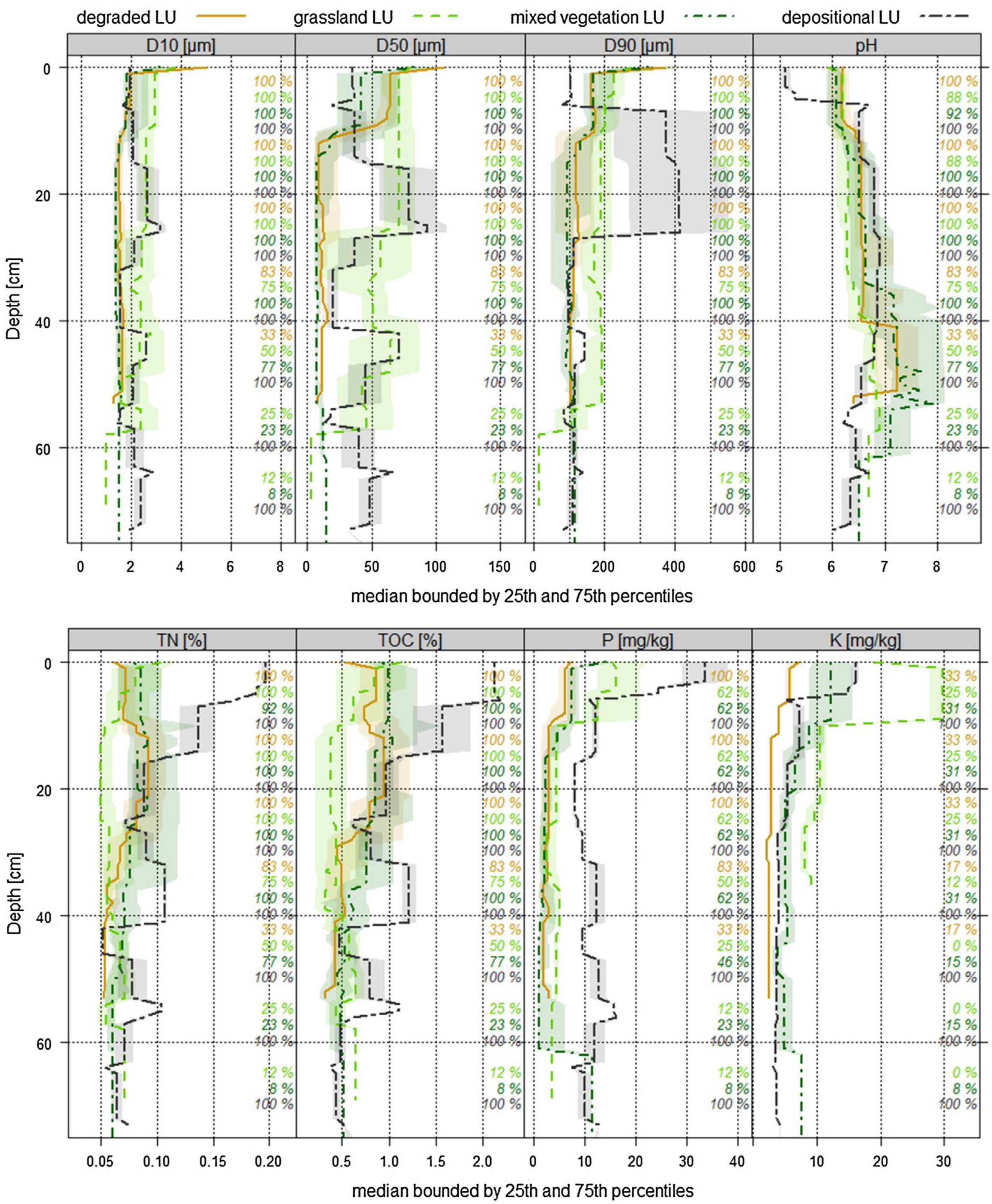

Fig. 5. Physico-chemical soil parameters for depth profiles of the different LUs (degraded LU N = 6, grassland LU N = 8, mixed vegetation LU N = 13, depositional LU N = 2). Percentages on the right side of the plots represent the contributing fraction of profiles per LU for 10 cm sections; colors are referring to the respective LUs. Note that for the depositional LU, only data from two profiles was collected, therefore, the trendline for the depositional LU represents the mean not the median value.

5. Discussion

5.1. Soil heterogeneity in southern African rangelands

Soils in the study area appear to be organised into a source-sink system which is mainly shaped by runoff and characterized by eroding and depositional areas (Sømme et al., 2009). This is especially evident when looking at features at the degraded sites, such as shrubs and tussocks growing on earth mounds, or silted-up reservoirs that are partially covered with different vegetation types when compared to the vegetation assemblage on the surrounding slopes (Krenz et al., 2019). Not all erosion features in the landscape are still active. Rills and small gullies are presumably partially stable, given the presence of established vegetation cover along their bases and (lower) sides. Land-use-induced erosion appears to be the most significant factor of soil formation at present.

Textural differences between the LUs were significant for the depositional LU, when compared to the three other LUs (Tables 2 and A1), whereas the depositional LU was characterized by larger proportions of fine material. Thus, it can be assumed that degradation and incision throughout the catchment are most likely not based on substrate differences, and degradation might have been induced after disturbance, by for instance, animal grazing or vegetation removal (Nouwakpo et al., 2016). Average D90 for the depositional area (134.92 μm) was about three times smaller than for all other LUs (346.97–407.87 μm) (Table 2), indicating that the fine material was trapped behind the reservoir dam. Looking at the spatial distributions of texture within the depositional LU samples, revealed that the finer samples were situated close to the former dam. Hence, a sorted distribution took place during sedimentation (McLaren and Bowles, 1985). The preferential deposition might have been masked by turbulence during runoff events or wind-induced waves over the reservoir surface (Greenwood et al., 2014). Variations in nutrient concentrations between degraded, mixed vegetation and grassland LUs appears to be independent of soil texture, given their similar characteristics. Consequently, any observed difference in nutrients is most likely due to effects of vegetation, and or erosion and deposition processes as substrate differences can be excluded.

Vegetated LUs (that includes depositional, grassland and mixed vegetation LU) had significantly higher TOC, TIC and TN contents than the degraded LU. Dryland soils are characterized by low amounts of nutrients (Vitousek, 2004) and biogeochemical cycles are largely controlled by water availability (Austin et al., 2004; Schimel, 2010). TOC and N are primarily linked to biological processes such as photosynthesis and microbial mineralization (Schlesinger et al., 1990; Vitousek, 2004) and litter input (Bochet et al., 1999; Snyman, 2005) which explains the low TOC content in the top 10 cm from the degraded profiles. Surprisingly, the vertical distribution of TOC and TN between 5 and 30 cm for the degraded and mixed vegetation LU was comparable and higher than for the grassland LU. This similarity could be attributed to randomness due to the small sample size of the degraded LU (N = 6) and grassland LU (N = 8). Another assumption could be that primary TOC might be preserved in the degraded LU due to its sparse vegetation and slow mineralisation in drylands (Austin et al., 2004). TOC in the grassland LU is constant in the deeper layers but shows indications of litter input in the top 10 cm of soil. In contrast to TN and TOC, available phosphorus is not exclusively derived by biological processes but by the deposition of atmospheric dust and rock weathering (Belnap, 2011). Thus, P contents were higher in top soils of vegetated LUs, where dust collects on plant leaves and stems. P input by animal faeces is another source of P in areas that are regularly grazed or where herd animals congregate (Bestelmeyer et al., 2006) and could explain the highest P content in the depositional LU. Exchangeable K did not differ significantly between LUs which might be attributed to the small sample size. Potassium is generally low in semiarid acidic soils and limited to the top soil as most of K is incorporated in minerals and desorbed and leached during rainfall events (Römheld and Kirkby, 2010). Potassium was slightly higher in vegetated areas, as nutrients are released by the mineralisation of organic matter (Barber, 1985).

Soil analysis has shown that the heterogeneous vegetation cover is reflected in heterogeneous chemical soil properties between areas affected by various degrees of erosion and degradation showing a disturbance of the natural soil catena, but also that the level of heterogeneity for certain physicochemical parameters within the same landscape units is high (Fig. 4).

5.2. To what extent is the spatial heterogeneity of the Sneeuberg soils reflected in conventional soil maps?

According to the international FAO soil classification (ISRIC, 2006), soils in the Sneeuberg area are characterised as lithic Leptosols. Leptosols are generally defined as shallow soils with (i) either a “continuous rock or technic hard material starting 25 cm from the soil surface”, or a less than 20 vol% of “fine earth averaged over a depth of 75 cm from the soil surface or to continuous rock, whichever is shallower”, and (ii) “no calcic, chernic, duric, gypsic, petrocalcic, petroduric, petrogypsic, petroplinthic or spodic horizon” (FAO, 2015). As a special case of Leptosols, the lithic Leptosols are even shallower and limited in depth by continuous hard rock at 10 cm. This might be true for hillslope soils of the Sneeuberg area, which were very shallow and had a large proportion of gravel or rock fragments that did not allow for any soil sampling. However, soils of the footslopes did not meet the shallow depth criteria of the Leptosol. Even though footslope soils were very compacted and cemented and it was not possible to excavate all pits until bedrock was reached, any bedrock would have been situated deeper than 25 cm and soils showed a greater proportion of fine earth material than those defined for Leptosols (ISRIC, 2006). Conventional maps for the study area were produced as part of national geological surveys, with the general purpose of mapping lithostratigraphic units and mineral deposits. They were not aimed at providing a national land use or soil fertility map which could be used for agricultural purposes at regional or local scales. However, depositional areas within the study area show much different characteristics than the lithic Leptosols per se. The problem of not-capturing the soil type in the most intensely used and degraded part of the study site is exacerbated by the observed variability of soil nutrient contents. They show a high spatial heterogeneity between degraded, vegetated, and depositional areas, which is not depicted in current soil maps, but is of significant relevance for soil protection measures and adequate management strategies (Paterson et al., 2015).

5.3. To what extent can anthropogenic soil erosion accelerate soil formation?

Besides the footslope soils that are mainly of a degraded nature, we suggest that there is a strong potential for the formation of young soils on the numerous silted-up reservoirs in the Karoo rangelands and other depositional sites along runoff pathways. Rapid reservoir sedimentation is not specific to the Karoo but a global problem and has been widely reported from e.g. Northern South Africa (Baade et al., 2012; Nde, 2015), Australia (Chanson and James, 1998), and Northern Ethiopia (Haregeweyn et al., 2008). While most rehabilitation strategies suggest sediment removal to preserve the water storage capacity (De Vincenzo et al., 2017) and to increase agricultural productivity with the deposited sediment (Haregeweyn et al., 2008), we suggest a direct use of the siltated reservoirs, e.g. as pasture. The Karoo reservoir soils are characterised by a deep profile depth (up to 5 m) and nutrient contents that are significantly higher than the natural soils.

An inadvertent consequence of the dams becoming infilled is that they now appear to act like nutrient oases in a dryland, by promoting the development of young soils that have notably higher-than-background nutrients. Since almost 50 % of the mapped farm dams in this region are silted-up (Boardman and Foster, 2011), young soils have the potential for use as highly productive grasslands. Farmers in the Karoo are aware of the greater quality of these young soils and are looking for ways to manage them sustainably (Jacobs, D., current manager of the study area, personal communication 2016; James, B., owner of a farm adjacent to the farm of the study area, personal communication 2019). Although spatially small in area, they support many palatable plants, offer rich grazing and act as gathering points for domestic livestock and game, and thus probably benefit from an increased manure input and thus nutrient supply. This also increases the infiltration potential and water storage capacity compared to soils in surrounding areas, especially if these are degraded. Both factors improve seed germination and seedling survival, because water availability in soils is a major limiting factor for plant establishment in semi-arid environments (Bochet et al., 2009). Since root penetration depth is not limited by the underlying bedrock, deeper rooting bush species might establish and bush encroachment could be a consequence. Most of the silted-up reservoirs in the area are vegetated, which increases the litter input and their nutrient content in the longer-term. Hence, although they cover only a small proportion of area, in our case 12 % of the study area, they presumably act differently in biogeochemical cycling than the surrounding shallow soils and should not be neglected in studies on local, regional and possibly global studies on biogeochemical cycles. While the silted-up reservoirs which might act as biogeochemical hotspots but only cover a very limited spatial extent, the flatter depositional areas in the valleys count for up to 40 % of the area in the Sneeuberg region. Thus, there is a relevant proportion of this area which cannot be classified as classic Leptosols and should be considered in regional soil maps.

5.4. How could azonal soils be considered in efforts to restore degraded drylands?

A successful rebuilding of a resilient ecosystem in semi-arid landscapes relies on the restoration of as many natural vegetation types as possible and a profound understanding of the landscape dynamics (Blignaut and Milton, 2005). The reservoirs in the Sneeuberg region are of small size and were mostly constructed for water storage in times of droughts or as check-dams (Keay-Bright and Boardman, 2006). Estimated sediment volumes per dam range from ca. 300 m^3 to about 323,000 m^3 (Boardman and Foster, 2011). Removing deposited reservoir sediment is not viable for most landowners, due to the high cost- and labour-investment. However, dam walls of a few reservoirs have been repaired, with the purpose to reuse them for water storage and to reduce surface runoff and downstream sediment transport (James, B., owner of a farm adjacent to the farm of the study area, personal communication 2019). Afforestation, as it has been shown to reduce downstream sediment yield in check dams in Spain (Boix-Fayos et al., 2008), is climatologically not possible in the Sneeuberg. However, a general increase of vegetation cover via shrub- or grassland could decrease runoff generation and stabilise the sedimentary dam structures in the long-term (Beguería et al., 2006; Wang et al., 2018). An emphasis on active soil management will also lead to soil quality improvements as a consequence of increased SOC and soil restoration. Based on the favourable conditions for plant establishment in silted-up reservoirs mentioned earlier, depositional areas immediately upstream of dams have the potential to act as C stores and facilitate C sequestration, as shown for check-dams in the Loess Plateau in China (Lü et al., 2012; Zhang et al., 2016). The dam density in the Sneeuberg area is high and represents the equivalent of 1 dam per km^2 (Boardman and Foster, 2011). With an average speculated storage potential of 20,000 m^3, an average TOC content of 1%, and an average bulk density of 1160 kg/m^3 a single dam potentially stores up to 232 t C. Considering that approximately 50 reservoirs are silted up, about 11.6 kt C could be stored in those Sneeuberg reservoirs that have been mapped thus far. These speculations should be treated with some caution, however, because long-term C sequestration can only be achieved if the dams remain intact and not breached. This is not the case for all reservoirs, as dam maintenance, or restoration of structures, will be necessary in order to stop current trends of dam breaching and sediment erosion (Boardman and Foster, 2011), especially when considering the predicted increase in rainfall intensity (Foster et al., 2012) and associated erosion, as a consequence of climate change.

Globally, drylands have a significant potential for C sequestration due to their large spatial extent and their unsaturated C content (FAO, 2004). With regard to rangelands of the Karoo, silted-up reservoirs in these areas should not be neglected as an important C storage, considering the wide distribution of dryland dams and their reduced potential of leaching dissolved C compared to wet soils or regularly irrigated soils as a lack of water (Glenn et al., 1993). The heterogeneous pattern of dryland soil properties demands more knowledge on their role in soil-atmosphere interactions and on the global C cycle. However, adequate management interventions that slow down or reverse degradation processes in drylands should be enhanced to maximise their potential for increased C sequestration.

6. Conclusion

This study on soil patchiness in a degraded Karoo landscape has illustrated the small-scale heterogeneity of soils in southern African rangelands, especially with regards to soils in depositional areas. Soils in the study area are not classic Leptosols, unlike those classified on soil maps. The main reason for this discrepancy is the spatial pattern of soil erosion and degradation that is not captured in soil maps. Chemical soil property patterns do not coincide with the vegetation cover, but show a high degree of variability within the same landscape units, especially for soil nutrients (TOC, TN and P). Sediments trapped behind dams can be identified as a depositional substrate where new and different soils can form and develop. They have a finer texture, are richer in nutrients, and their profile is deeper than both the Leptosols and the degraded soils observed in the valley. The improved water supply and unimpeded root growth also offer more favourable conditions for vegetation and pastoral land use than naturally occurring soils in the Karoo. The large number of silted-up reservoirs in the Sneeuberg region, as well as in other semi-arid areas (Chanson and James, 1998; Elmouden et al., 2017; Haregeweyn et al., 2012, 2008, 2006), potentially leads to the development of such anthropogenic soils on a significant proportion of rangelands. Their improved water and nutrient supply promote plant growth and use for grazing. Water and nutrients potentially promote turnover rates in biogeochemical cycles, creating hotspots of soil-atmosphere interaction in drylands, similar to wetlands in more humid climatic conditions. Therefore, the biogeochemistry of these young anthropogenic soils forming behind dams should be more comprehensively explored.

The results of this study also show that understanding soil patchiness is essential for managing rangelands sustainably, both locally, but also in the context of their relevance for global biogeochemical cycles. It is therefore essential to develop tools for mapping rangeland soils at an appropriate spatial scale. Once the soil formation and patterns are understood, it is essential to identify spatial covariances between the patchwork of soils and controlling factors such as topography and vegetation. Based on covariances which can be applied across larger spatial scales maps with a more realistic representation of soils and their function in the environment can be developed using remote sensing data, elevation models and vegetation indices.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A

Table A1
Kruskal-Wallis (column 1) and pairwise comparison results (column 2-6) for differences between top soil samples from landscape units (LU). Column 1 shows the p-values for the Kruskal-Wallis test. The number after the chi-squared χ^2 report the degrees of freedom and the number of samples analysed for each variable. -Significant results at the 0.95 level are presented in bold. Please note that for P and K a smaller sample size was analysed (see description Table 2).

	All Landscape Units (LUs)	Depositional and Degraded LU	Depositional and Grassland LU	Depositional and Mixed Vegetation LU	Degraded and Grassland LU	Degraded and Mixed Vegetation LU	Grassland and Mixed Vegetation LU
D10	χ^2 (3, 51) = 3.39, p = 4.40E-01	8.50E-01	1.00E-01	5.80E-01	2.90E-01	5.40E-01	2.90E-01
D50	χ^2(3, 51) = 2.70, p = **3.78E-04**	**4.40E-03**	**6.80E-04**	**2.10E-04**	8.10E-01	2.70E-01	1.00E+00
D90	χ^2(3, 51) = 18.32, p = **9.84E-07**	**5.00E-03**	**2.10E-04**	**5.70E-06**	1.80E-01	1.80E-01	7.40E-01
TOC	χ^2(3, 51) = 29.07 p = **2.16E-06**	**1.70E-05**	3.40E-01	7.60E-02	**1.50E-04**	**4.00E-05**	1.20E-01
TIC	χ^2(3, 51) = 37.92, p = **2.94E-08**	**4.40E-06**	**1.60E-02**	**7.90E-05**	**2.60E-03**	**8.40E-05**	**2.20E-02**
pH	χ^2(3, 49) = 24.97, p = **1.62E-05**	**1.00E-02**	**8.20E-03**	**3.00E-05**	5.60E-02	**3.90E-03**	9.50E-01
TN	χ^2(3, 51) = 21.23, p = **9.46E-05**	**7.20E-05**	8.10E-02	1.00E-01	**1.20E-03**	**6.10E-03**	2.90E-01
P	χ^2(3, 38) = 26.44, p = **7.71E-06**	6.70E-02	1.80E-01	5.00E-02	**8.10E-03**	**1.00E-02**	3.40E-01
K	χ^2(3,10) = 6.67, p = 8.30E-02	2.50E-01	2.50E-01	3.50E-01	4.10E-01	2.50E-01	1.10E-01

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2021.100290.

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