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A perfect storm: unprecedented expansion of the Namib Desert and cascading desertification processes in the northernmost Succulent Karoo

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A R T I C L E I N F O

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A B S T R A C T

Arid regions are characterized by high unpredictability of rainfall. Consequently, ecosystems along their margins are naturally oscillating but usually resilient. Here, we report the severe and potentially irreversible degradation of vegetation, ecosystems, and biodiversity in the northernmost more than 1 million ha of the Succulent Karoo, a global biodiversity hotspot. In our study, we use monitoring data spanning 45 years to disentangle different processes of change which started decades ago. The regionally important, vulnerable ecosystem “Gariep silty plains” is inhabited by the species-rich vegetation alliance Brownanthion pseudoschlichtiani. The cushion-like dwarf shrub scorpionstail (Brownanthus pseudoschlichtianus, Aizoaceae) is the dominant plant species protecting the soil and facilitating silt sedimentation. Following disturbances, this vegetation type is thinning and losing perennial plant species. This allows aeolian erosion, which – as a tipping point - turns the silty topsoil into sandy soil across extensive areas. Increased mobilisation of aeolian sand causes abrasion and sedimentation, which buries vast landscapes. The newly developed sandy topsoils are invaded by species-poor grassland communities partly typical for the Namib Desert biome. We present a novel S&T model and discuss cascading effects which threaten nature, farmland and infrastructure. Farming, mining, road construction and climate change may be interacting drivers of degradation.

1. Introduction

Global drylands cover more than 45 % of the global terrestrial ecosystems and can be regarded as the largest biome on this planet (Schimel, 2010). Drylands often experienced large-scale extreme changes of vegetation. The margins of deserts and semi-deserts are especially subject to change over longer periods of time. Paleo-environmental studies have shown dramatic changes of vegetation during the Holocene. For example, most of the eastern Sahara was an arid savannah until 7.000 years ago and turned into the present large desert within a few thousand years (Kuper and Kröpelin, 2006). Similarly, in the western parts of southern Africa, the boundaries between Fynbos, Succulent Karoo and Namib Desert shifted by several hundred kilometres in a north-south direction, during and after the last glaciation (Scott et al., 2004, 2012).

Natural climate changes drove such changes in the past, and it is highly probable that such changes will gain momentum now, in times of accelerated climate change and human land use. Anthropogenic impacts of farming, like overgrazing (Reynolds et al., 2007), mining, and growth of settlements, make desertification processes more likely.

In published literature, the impact of strong grazing pressure on vegetation has often been reported (e.g. Todd and Hoffman, 1999; Riginos and Hoffman, 2003; Hoffman and Rhode, 2007, Hoffman et al., 2018a and b). However, we did not find reports for larger shifts of the desert boundaries in the southern African drylands during the last 200 years (Hoffman et al., 2009). Rather, farmers in Namibia and South Africa regard series of wetter or drier years as reversible oscillations. This rather supports the view that desertification-prone ecosystems can

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be very resilient (Bestelmeyer et al., 2013).

The Succulent Karoo, which has early been recognized as one of only two arid global hotspots of biodiversity (Mittermeier et al., 1998, 1999), has even been regarded as an arid ecosystem with relatively low variability of the annual rainfall, 20 % more predictable than the more unpredictable Nama Karoo (Desmet, 2007). Analyses of the climate history in the Succulent Karoo found no evidence for a decrease either in mean annual rainfall or in the incidence of drought over the 20th century (Hoffman et al., 2009). On the other hand, modelled projections of climate change indicate an increase in aridity and project changes of vegetation and biodiversity for most of the ecosystems adjacent to the Namib Desert (Midgley and Thuiller, 2007, 2011). Global analyses which found positive effects of grazing in colder and species-rich areas (Maestre et al., 2022) did not consider a single study site in the entire Succulent Karoo or Southern Namib Desert.

The dynamics of vegetation, driven by environmental variability and by endogenous factors, have been studied in more humid parts of the Succulent Karoo, in Namaqualand, by Milton and Hoffman (1994); Hoffman et al. (1999); Todd and Hoffman (1999); Van Rooyen et al. (2015); Hanke et al., 2014; Samuels et al., (2019); Schmiedel et al., (2023); Schmiedel and Oldeland (2018); Geldenhuys et al. (2023) analysed the changes during the prolonged drought from 2015 to 2022 and discussed the involvement of both, equilibrium and non-equilibrium vegetation dynamics.

Until now, such and other hypotheses have not been based on robust observations and process analyses in the more arid, northwesternmost tip of the Northern Cape of South Africa, at the margin of the biome's boundary. The objective of the current study is to address such knowledge gaps within the over 1 million ha of the Richtersveld (Fig. 1). In spite of large protected areas, small stock pastoral land use and mining are allowed in most of the Richtersveld. This study tests previous hypotheses concerning degradation by presenting empirical evidence from 59 sites collected over 45 years of long-term monitoring across an extensive area affected by mining, farming, and climate change.

2. Methods

We established a database with diverse sources of evidence of biogeophysical changes based on vegetation monitoring, repeat photography and comparisons of satellite imagery. By examining these across a complete prolonged drought cycle, we were able to differentiate different agents and processes of degradation, including the roles of vegetation type, soil, climate change, and anthropogenic impacts.

We focused on monitoring on the Brownanthion pseudoschlichtiani alliance (Jürgens, 2004) because it is widespread and occurs across a large environmental gradient. The associations of this alliance are dominated by *Brownanthus pseudoschlichtianus* S.M.Pierce and Gerbaulet (synonym *Mesembryanthemum pseudoschlichtianum* (S.M.Pierce and Gerbaulet) Klak), a stem and leaf succulent dwarf shrub of the family Aizoaceae, locally named "scorpionstail". This succulent dwarf shrubland (here called "scorpionshrubland") occurs on the "Gariep silty plains" ecosystem, in the lowlands between the coast and the escarpment (locally called Sandveld), and also on the plains in the valley bottoms, the inner-montane basins in the Richtersveld mountains, as

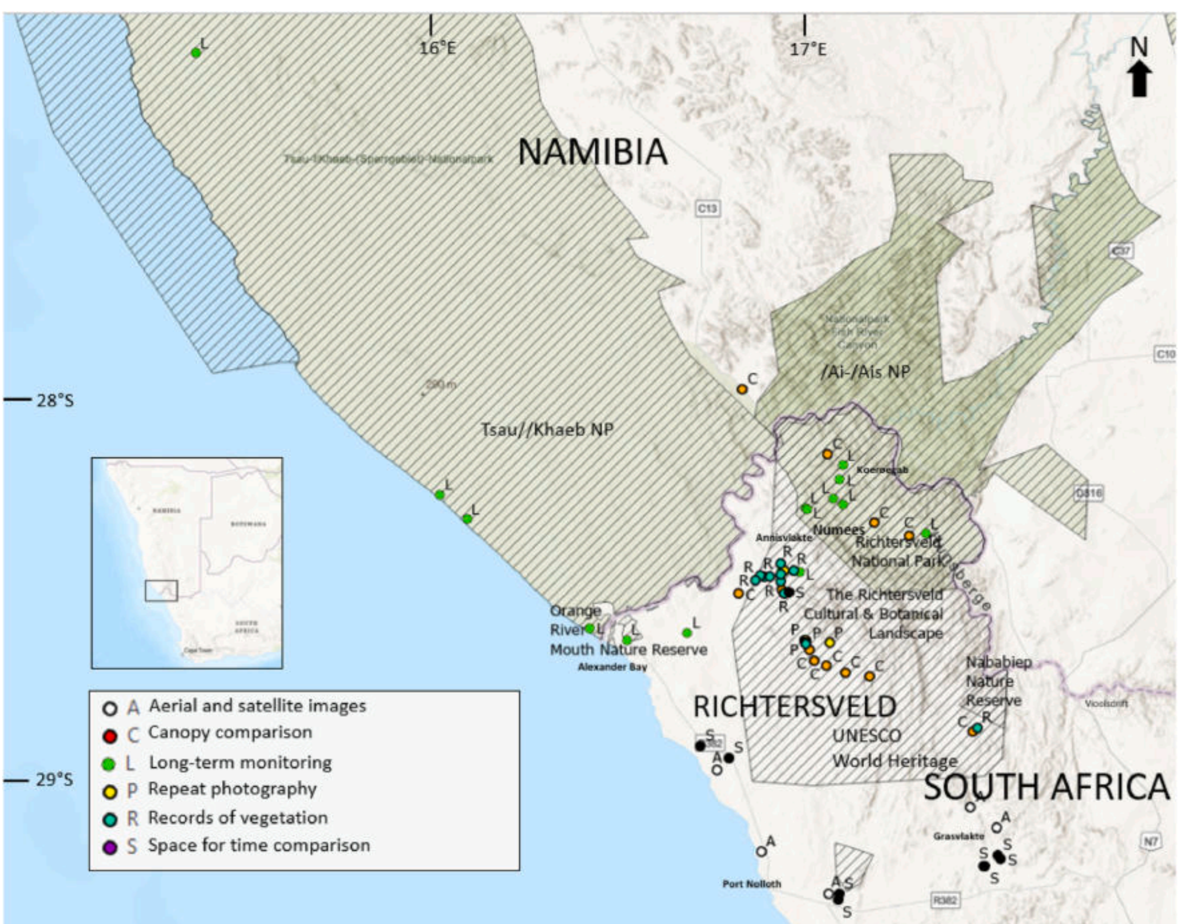

Fig. 1. Map of the Richtersveld (south of the Orange River bend, east of the tar road N7 Vioolsdrift-Steinkopf, north of the tar road R382 Steinkopf-Port Nolloth), with conservation areas (oblique hatching) and study sites. Map data by Esri, CGIAR, Esri South Africa, TomTom, Garmin, Foursquare, FAO, Meti/NASA, USGS, DEA SAPAD, Atlas of Namibia) (NP=National Park). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

well as in the Tsau//Khaeb National Park in Namibia (Jürgens, 1986, 2004; Gotzmann, 2002; Nussbaum, 2003; Oguz et al., 2004).

For the assessment of vegetation change, we used data from long-term monitoring established stepwise since 1980, continuing until the present. A "relevé" is a complete assessment of the plant species composition of a homogeneous subset of the vegetation at a given date within a permanently marked surface area of a defined dimension, mostly 100 m^2, called "plot". For each plant species, the percentage of cover within the plot area and a count of all individuals (abundance) is recorded, the latter number in stepwise coarser resolution with growing numbers, exact up to ca. 50, then counted in tens, hundreds, thousands, etc. Within the plots, the height, largest diameter and position of all perennial plants are also recorded to track the life-histories of the individuals. Tables present the cover values in %, often followed by abundance in brackets (number of individuals/1000 m^2). Values of dead plants are sometimes shown in square brackets. In case of historical photos, a question mark is used to indicate that the photo does not allow the identification or quantification of a given species.

We distinguish seven different types of information:

1. **Long-term monitoring plots with annual time intervals (L) (n = 7)** provided the most detailed information. Most of these sites were established in the mountains of the Richtersveld National Park. For this type of data, a complete list of species, cover values and, for most, numbers of individuals and photo records exist.
2. **Monitoring plots with sporadic visits (L) (n = 7)** provided the same data as long-term monitoring plots but with gaps of one to several years interrupting a continuous time series.
3. **Repeat records of relevés at different points in time (R) (n = 13)**: Releves were resurveyed at some point in time during our vegetation studies since the 1980s. These plots allow comparison of time-series records at the same place. For this type of change analysis, we usually noted cover values of the plant species, sometimes accompanied by abundance (numbers of individuals). The loamy plains, inhabited by scorpionshrubland are well-defined habitat patches, typically with relatively homogeneous vegetation that is visibly differentiated from the surrounding habitats. Therefore, in a few cases, we compare a releve taken after the drought to a historical plot recorded within 200 m from the most recent plot.
4. **Repeat photography (P) (n = 5)**: A photographic record at a retrievable location allows comparison with a current record at the same place, consisting of a repeat photo and a full vegetation record as a relevé (see below). For this type of change analysis, cover values and sometimes the number of individuals was used. Species that could not be assessed based only on a photo were listed with a question mark.
5. **Reverse assessment based on dead canopy (C) (n = 12)**: With less depth in time, current records at former scorpionshrubland sites allowed comparison with the extent of the scorpionshrubland before the drought, based on the dead standing canopy of above-ground biomass of *Brownanthus pseudoschlichtianus.* The cover of the dead canopy was invariably attributed to the year 2014, the last year in which scorpionstail plants grew and produced side branches. While the cover of dead canopy of *Brownanthus pseudoschlichtianus* could be assessed, numerous other species which did not leave such a trace were noted with question marks.
6. **"Space for time" comparison (S) (n = 9 pairs or triplets of relevés)**: We observed the expansion of a sand sheet into a vegetation type, which got buried under the sand. Where narrow bands of mobile sand advanced into the vegetation we compared (a) a relevé in the vegetation not damaged by invading sand with (b) a nearby relevé in the vegetation after it was buried under sand. Sometimes the vegetation in a transition zone with less imported sand was also assessed. Such a "space for time" comparison was assessed in the same year.
7. **Time series of satellite images (A) (n = 5)**: We show several time series of satellite images (provided by Google Earth based on Maxar Technologies, Landsat/Copernicus, CNES Airbus) in order to provide evidence for the causative role of various drivers. Ground truth was added by relevés recorded within the original and altered vegetation. Some of these time series could not be ground truthed because of restricted access.

3. Results & discussion

A total of 59 study sites (54 in South Africa, five in Namibia) provide information on the change of vegetation in time in the region, covering all types of scorpionshrubland and the entire range of scorpionstail within the Richtersveld and adjacent Namibia (Fig. 1). Baseline data for the 59 study sites are presented in Tab. SOM 54 and SOM 55 (SOM = in Supplementary Online Material). More detailed evidence for each study site is provided in supplementary online material (SOM). In the following, we 1. introduce the reader to the states of degradation which we found within the study region, 2. describe the timeline and patterns of decline and recovery, 3. discuss the processes of degradation and their spatial distribution as well as 4. the role of different drivers and, 5. principles for conservation, adaptation and mitigation.

3.1. States of degradation

During 45 years of monitoring the processes of change within scorpionshrubland repeatedly showed a spectrum of states that sequentially replace species-rich scorpionshrubland. In the majority, i.e. 39 of those 40 study sites, where quantitative records for scorpionstail were available (see Table SOM 55, column BII), scorpionshrubland either experienced reductions in cover and species number or *Brownanthus pseudoschlichtianus* was replaced by other species. In several cases, the destruction of scorpionshrubland even resulted in bare ground. The strongest changes were found where the species pool and the vegetation types of the Succulent Karoo were replaced by new plant communities, which were formerly known from the Desert Biome.

We found the full sequence of degradation spanning from healthy scorpionshrubland to bare ground or even desert grassland all over those parts of the Richtersveld which carry scorpionshrubland. However, the degradation states in between the extremes, i.e. after degradation of the Brownanthus pseudoschlichtianus population and before the deterioration to bare ground or desert grassland, show some variation within certain parts of the Richtersveld. To capture these variants, we distinguish four "degradation sequences", labelled as I to IV (see Tab. SOM 54, column 4 = Degradation sequence). In the following, we introduce these degradation sequences with their typical degradation states.

The geographical occurrence of the four degradation sequences (I – IV) and the degradation state of each study site as for 2024 are shown in Fig. 2. These states are illustrated with photos in Fig. 3 and a schematic overview of the states and the involved processes and drivers is presented in Fig. 4.

3.1.1. Degradation sequence I

Degradation sequence I is the most widespread sequence that is found in the various landscapes of the Richtersveld. We present the seven states in a sequence of increasing degradation, from healthy scorpionshrubland to bare soil or desert grassland:

State 1: Healthy scorpionshrubland: Brownanthion pseudoschlichtiani alliance in good condition with higher cover and species numbers (10- >40 species, 3–15 perennials/100^2) (Jürgens, 1986; Gotzmann, 2002; Nussbaum, 2003; Jürgens, 2004; Oguz et al., 2004; Jürgens et al., 2010). Cover of *Brownanthus pseudoschlichtianus* mostly ≫ 10 %. (Fig. 3.1).

State 2: Degraded scorpionshrubland: Brownanthion pseudoschlichtiani alliance with decreased cover and species numbers. Cover

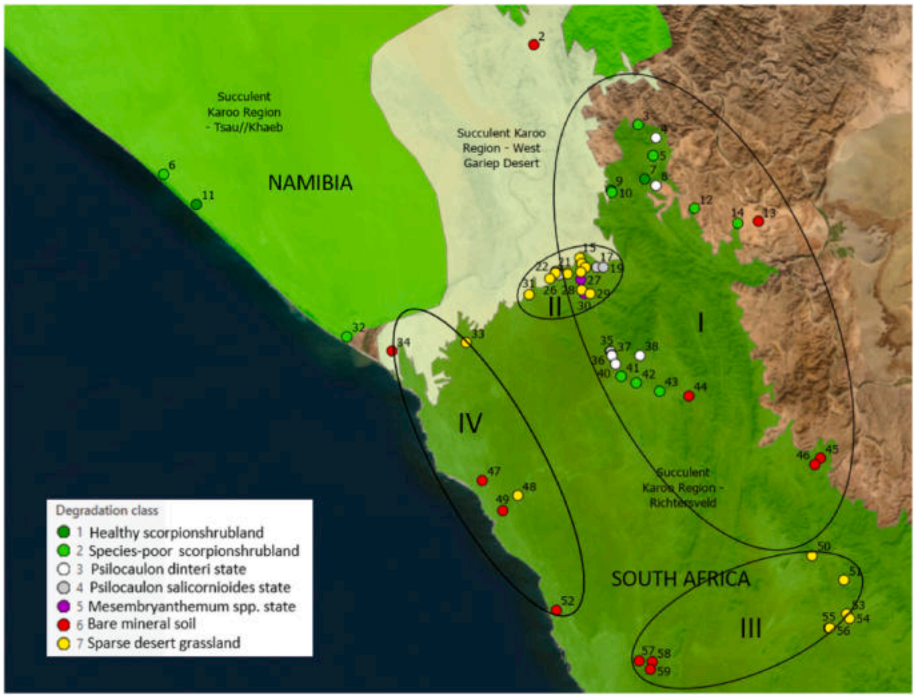

Fig. 2. Distribution of study sites and their state of degradation in 2024. Black ellipses indicate degradation sequences I, II, III and IV in the Richtersveld. Background colours show the area of the Succulent Karoo region: darkest green, partly following SANBI (2024), grass green and lightest green following Jürgens et al. (2006) (in Namibia a first approximation, excluding dunes and sand sheets, which needs further field mapping). Source of satellite image provided by ESCRI ArcGIS Pro: Earthstar Geographics. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of *Brownanthus pseudoschlichtianus* < 10 %, sometimes only 0,01 %, i. e., one or a few plants (Fig. 3.2). Compared to state 1, mainly perennial species dropped out resulting in species-poor conditions (<10 species, <3 perennials/100 m^2).

State 3: Psilocaulon dinteri - state: After the loss of *Brownanthus pseudoschlichtianus*, only very few perennial species remained (n = 2 to 3), the most frequent being *Psilocaulon dinteri*, often accompanied by *Drosanthemum inornatum* and/or *Psilocaulon salicornioides* (Fig. 3.3).

State 4: Psilocaulon salicornioides - state: This state, with even fewer perennial shrub species (1–3/100 m^2), lacked *Psilocaulon dinteri* and *Drosanthemum inornatum*, while *Psilocaulon salicornioides* was the only or most important perennial shrub (Fig. 3.4).

State 5: Mesembryanthemum spp. - state: This state was only seen in years with sufficient precipitation. In dry years, these sites were assessed as state 6 (bare mineral soil). After the loss of almost all perennial shrubs, annuals cover the soil in years of good rainfall (Fig. 3.5). Mainly four species of Mesembryanthemum (*M. barklyi*, *M. hypertrophicum*, *M. pellitum*, *M. gariusianum*) reach large biomass and protect the soil against wind erosion. These species are pioneer plants and generally known to occur in abundance at disturbed sites, for example stock posts, where they cope with high soil salinity.

State 6: Bare topsoil - state: Without good rains, the degradation reached the biological minimum and the mineral soils were completely uncovered, with various proportions of silt and sand, depending on the wind regime (Fig. 3.6). Note that stage 6 in some cases could also become stage 5, if observed after good rains.

State 7: Sparse desert grassland: A shift to a new vegetation type was reached when former scorpionshrubland vegetation was replaced by sparse desert grassland (Fig. 3.7). Typically, this was accompanied by a change of topsoil from silty to sandy texture. The most frequent grass species on sandy soil is *Stipagrostis ciliata*, often accompanied by *Schismus barbatus*, *Stipagrostis obtusa* was more frequent on calcareous soils, with high intensities of sandblasting indicated by the presence of *Stipagrostis subacaulis* (Fig. 3.7) and in one study site *Stipagrostis sabulicola*, as first find ever made in South Africa. The first three species are widespread, while the last two are proper endemics of the Namib Desert and the last one represents a range expansion, against the prevailing wind.

In this sequence of increasing severity of degradation, states 1 to 6 can be regarded as states of Succulent Karoo vegetation and Succulent Karoo ecosystems. Even the bare mineral soil (state 6) can be re-inhabited at least by annual species of the Succulent Karoo if the soil has sufficient silt. The transition to sparse desert grasslands (state 7) represents a real regime change: a new vegetation type and a new ecosystem (desert grassland of the desert biome) in locations previously characterized as Succulent Karoo.

3.1.2. Degradation sequence II

Degradation sequence II is very similar to sequence I, but characterized by the presence of a population of *Euphorbia gummifera* and the absence of the states with *Psilocaulon* species. A good example of the sequence II is a time series in the Annisvlakte, which starts with a historical photo taken in 1914 (Site no. 18 = Plot 16900, -28.45755 °S, 16.90873 °E). At that time, the Brownanthion pseudoschlichtiani alliance with some *Euphorbia gummifera* (state II.1) was clearly developed (Fig. 5.1). This *Brownanthus pseudoschlichtianus* shrubland was heavily degraded probably due to overgrazing in combination with increased wind and sandblasting. More than nine decades later (2003) *Brownanthus pseudoschlichtianus* had disappeared, and the area was dominated by the stem succulent shrub *Euphorbia gummifera* (state II.3, Fig. 5.2). Another two decades later (2024), the area had turned into sparse desert grassland (state II.7, Figs. 5.3 and 4).

This example shows that within 111 years, the vegetation was transformed twice into completely different plant communities (see Table 1). Dense scorpionshrubland, which offers good pasture, was replaced by toxic spurge shrubland, which was, in turn, replaced by sparse desert grassland with saline annual *Mesembryanthemum* plants (soutslaai = salt salad). An abundance of fossil *Euphorbia rhombifolia*

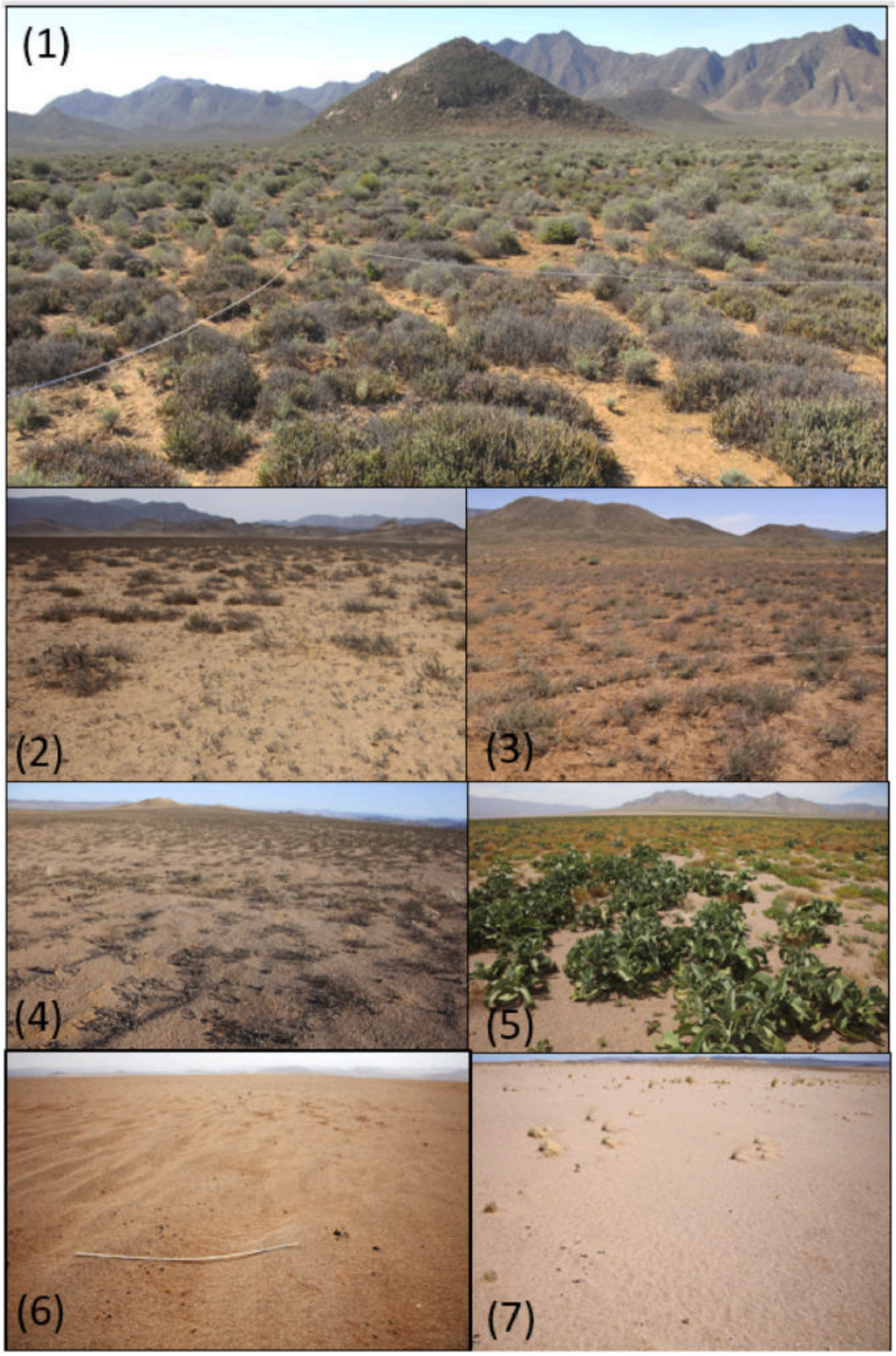

Fig. 3. Sequence I of degradation states of scorpionshrubland. 1 = state 1: Healthy species-rich Brownanthion pseudoschlichtiani alliance (Koeroegabvlakte, October 09, 2010, before the drought). 2 = state 2: Species-poor scorpionshrubland. *Brownanthus pseudoschlichtianus* and *Aridaria serotina* are the only perennial species (Gai Gas Vlakte, October 03, 2024.3 = state 3: High density of *Psilocaulon dinteri* shrubs (Dipkraal, October 20, 2024). 4 = state 4: *Psilocaulon salicornioides* is the only perennial species (Annisvlakte, October 03, 2024). 5 = state 5: After good winter rains, the soil is covered with *Mesembryanthemum barklyi* (large leaves), *Mesembryanthemum hypertrophicum* and other annual herbs (Annisvlakte, October 03, 2024). 6 = state 6: Bare sandy soil, where only the black remnants of *Euphorbia rhombifolia* indicate a history of previous vegetation. Note the mega-ripples in the coarse sand indicating very high wind speeds (Annisvlakte, October 10, 2022). 7 = state 7: Tussocks of *Stipagrostis ciliata* form a sparse desert grassland. Note the blackish remains of former *Euphorbia rhombifolia* stumps, indicating the former presence of a species-rich vegetation (Annisvlakte, October 10, 2022).

stumps indicated an even longer history of vegetation change.

3.1.3. Degradation sequence III

Degradation sequence III is characterized by scorpionshrubland being buried under aeolian sand. For the corresponding species lists of healthy and degraded states see SOM Tab. 50, 51, 52 and 53. As an example, we show a time series of satellite images in Fig. 12 and a sequence of photos in Fig. SOM 130 to SOM 150. Fig. SOM 147 shows the still undamaged vegetation of state III.1. Fig. SOM 148 and SOM 149 show the sand-covered state III.3, Fig. SOM 150 the final state III.6 with dead remains of the former vegetation.

This sequence is placed in Fig. 4 as the third column. Compared to the processes in column I and II, the burying under sand is a rapid process which sometimes immediately results in bare sand. In some

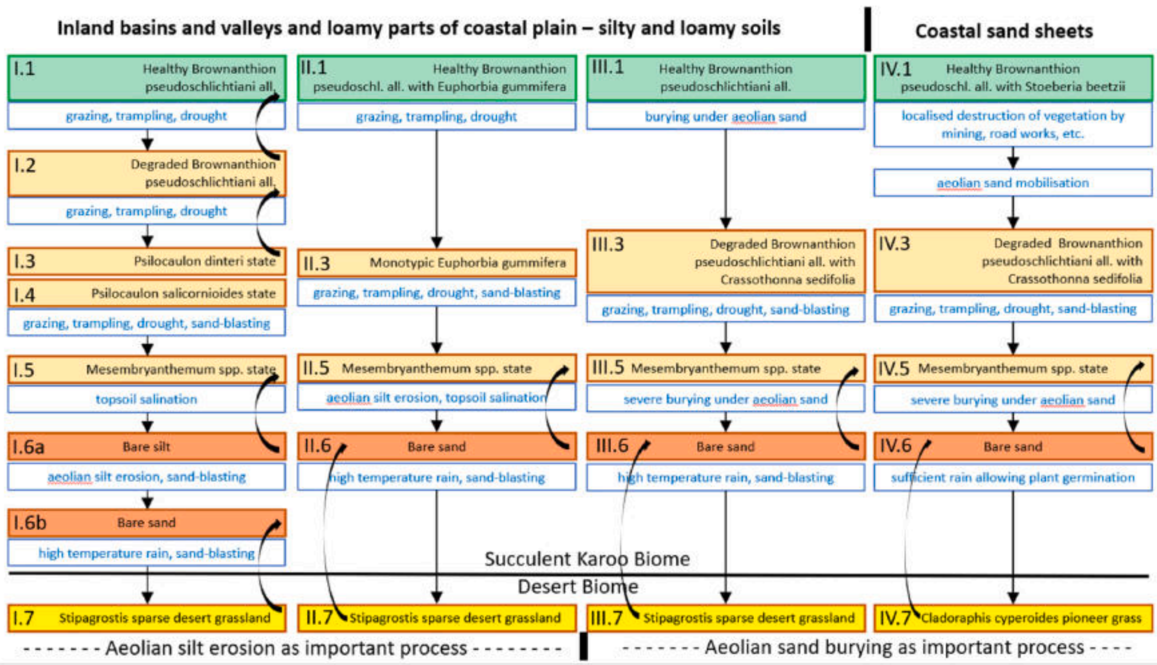

Fig. 4. Schematic state and transition graph showing the sequences of states of degradation within scorpionshrubland and the drivers and processes associated with the transitions. The states of increasing degradation are shown in boxes filled with colours and marked by the Arabic number. The typical scorpionshrubland with the most frequently found sequence of states is listed in the first column on the left side (sequence I). The three columns further to the right in Fig. 4 show the slightly different sequence of states found in specific scenarios. The second column (sequence II) presents the slightly different degradation states observed in sites which carry a population of the tall stem-succulent shrub *Euphorbia gummifera* (frequently found in the northern Richtersveld), while the states with *Psilocaulon* species are absent. In the third column sequence III represents the states observed in landscapes where scorpionshrubland is buried under aeolian sand (frequently found in the southern Richtersveld). In sequence IV we list the states observed in the white and yellow sands of sand sheets and dunes near the Atlantic Ocean coast. In sequences I and II, degradation is caused by grazing, trampling, drought, strong winds and associated sand abrasion, silt erosion and heat. In the sequences III and IV, sand burying occurs in the context of mining and road construction, as well as (over)grazing. Note the few reversible transitions between states 1, 2 and 3 and between 5, 6 and 7. The transition from more or less degraded Succulent Karoo vegetation on silty soils (states 1, 2, 3 and 4) to the states 5, 6 and 7 on sandy soils is irreversible. Of course, desert grassland (7) may be devoid of any vegetation in dry years (6) or may experience germination of annual Mesembryanthemum species (state 5) after good rains, hence the arrows indicating these "backwards" transitions. The abbreviation "all." Stands for "alliance". (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cases, we found the temporary states III.3 and III.5, often located at the margin of the invading sand plume.

In 2023 and 2024, there was a clear-cut frontline between the undamaged original vegetation and the advancing sand plumes, as shown in Fig. SOM 129, 132, 133, 136, 143, 146 and 147.

3.1.4. Degradation sequence IV

Degradation sequence IV is similar to III, however, located close to the Atlantic Ocean. Therefore, different species are involved (see Tab. SOM 32, 34, 35, 47 and 48). In the coastal sand *Cladoraphis cyperoides* is the typical grass species which replaces former Succulent Karoo dwarf shrubland. A good example for sequence IV is a *Stoeberia beetzii-Brownanthus pseudoschlichtianus* shrubland on loamy sand, (Fig. SOM 123 to 126 and Tab. SOM 48) which is buried by sand mobilized by the construction of the tar road between Port Nolloth and Alexander Bay (Site no. 48, −28.92805 S, 16,77329 E).

Irrespective of the sequence, the states of degradation were not equally distributed in 2024 over the studied area (Fig. 2). The intact and the less degraded sites (greenish to whitish colour) are found in the mountainous areas in the northeast and in the apron of the Ploughberg, which also receives higher precipitation from a south-westerly direction. The severely degraded sites (red, yellow) were mainly found in the lowlands west of the mountains.

3.2. Timeline and patterns of decline and recovery

3.2.1. Course of the centennial drought

To interpret the changes in vegetation, it is important to look at the recent history of drought and more humid periods. The year 2019 was the peak of the longest and most intense drought ever recorded in the Richtersveld since 1902. In the northernmost Richtersveld, the drought extended until the end of 2022. Because of the unprecedented intensity and length, we refer to this as the "centennial drought". The course of the Standardised Precipitation-Evapotranspiration Index (SPEI), calculated at the 36-month scale, underlines the dire severity of the drought: Never before had the index remained for so long at such extreme negative values (Fig. 6).

A look at the rainfall alone, compiled for 1980 until 2024 at Numees (Fig. SOM 151), shows that eleven consecutive years (2009–2022) received rain below the average of 89.28 mm mean annual precipitation (MAP, 1980–2024), with 2017–2019 having even less than 50 % of MAP.

3.2.2. Vegetation changes during and after the drought

Fig. 7 shows the course of several species of a plot at an inter-mountain valley (site no. 9, plot 3, Numees) during 1980–2024. The red curve shows the cover value of *Brownanthus pseudoschlichtianus*. The courses of rainfall and scorpionstail cover show several parallels at a coarse scale. For example, the good rain years 1992–1997 and again 2005–2008 are reflected by high cover values, while the low cover of 2004 followed a very dry year 2003. Cover declined extremely during the centennial drought, starting after 2014, being almost zero in 2018 and 2019, and recovering since 2020.

A higher resolution of the effect of the centennial drought on the scorpionshrubland vegetation can be based on a synopsis of those four of eight replicates of scorpionshrubland long-term monitoring sites which

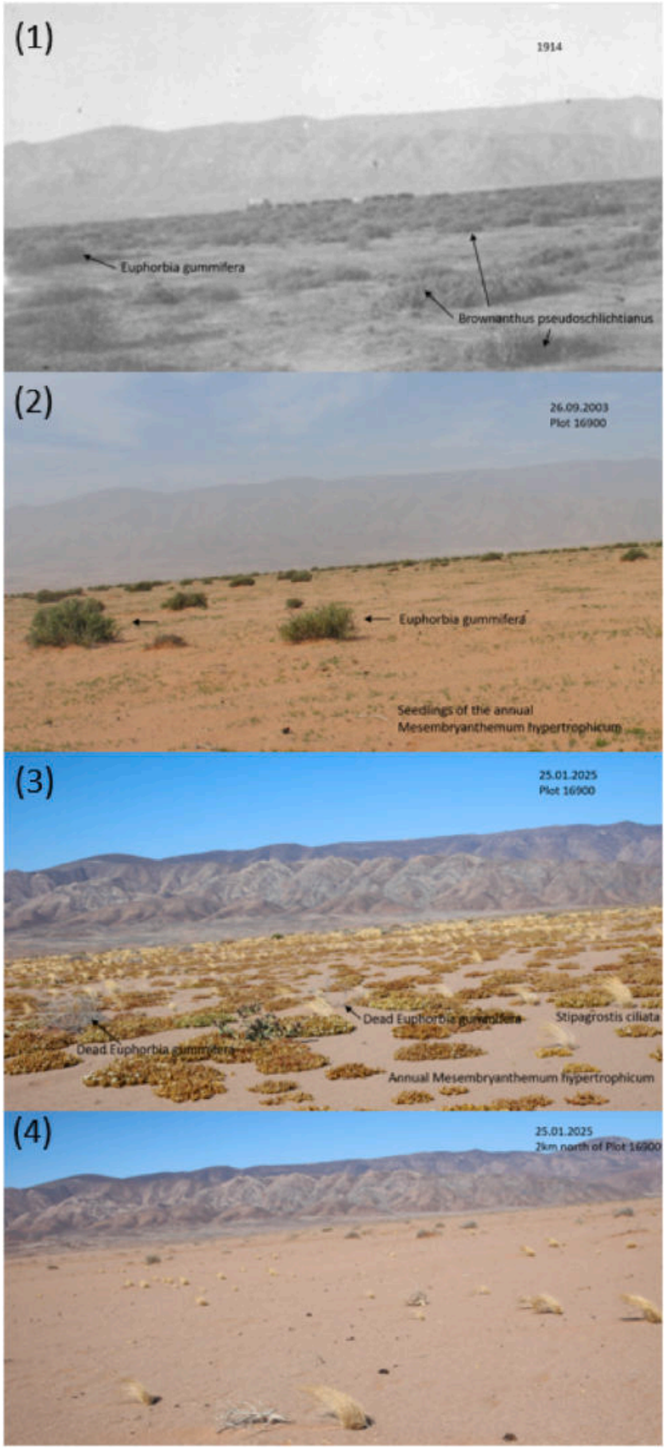

Fig. 5. Severe vegetation change from rich Succulent Karoo to sparse desert grassland in 111 years (site 18). (1): The historical photo from 1914 shows typical scorpionshrubland (degradation sequence/state II.1) in the Annisvlakte (Photo Credit: Fred Cornell). (2) In 2003 the exact locality was found and marked as monitoring site no. 18 = plot 16900. *Brownanthus pseudoschlichtianus* was no longer present. A population of *Euphorbia gummifera* formed the dominant vegetation. Note the numerous *Mesembryanthemum hypertrophicum* seedlings. (3) The same spot on January 25, 2025. Degradation state II-7: All *Euphorbia gummifera* shrubs had died, and no more obligate perennial shrub species were found. Note the invasion of desert grasses and annual *Mesembryanthemum* species, which increase topsoil salinity. (4) Only few tussocks of desert grassland remain when the *Mesembryanthemum* spp. have died.

Table 1
Plant species recorded in site no. 18 (plot 16900), listed as percent cover [%] or density [N/1000 m^2]. See chapter "methods" for further explanations. This table is shown in the main text, because of the extraordinary length of timeline. All other vegetation tables are shown in SOM.

Species	1914	2003	2024
Brownanthus pseudoschlichtianus	20 %	–	–
Euphorbia gummifera	0,1 %	2 %	–
Asparagus capensis	?	0,1 %	–
Monsonia ciliata	?	0,1 %	–
Salsola zeyheri	?	0,1 %	–
Ledebouria undulata	?	0,01 %	–
Dipcadi brevifolium	?	0,01 %	–
Zygophyllum cordifolium	?	0,1 %	–
Mesembryanthemum hypertrophicum	?	3 %	5 % (900)
Foveolina dichotoma	?	0,1 %	0,1 (13)
Mesembryanthemum barklyi	?	0,1 %	0,1 % (30)
Stipagrostis ciliata	?	0,1 %	0,1 % (40)
Stipagrostis obtusa	?	0,01 %	0,01 (4)
Stipagrostis geminifolia	?	0,1 %	0,01
Stipagrostis subacaulis	?	–	0,1 % (80)
Stipagrostis namaquensis	?	–	0,01 % (1)
Schismus barbatus	?	–	0,01 % (2)
Kewa salsoloides	?	–	0,1 % (3)
Trianthema parvifolium	?	–	0,1 (1)
Total cover of perennial shrub species:	**20,1 %**	**2,6 %**	**0,0 %**
Total cover of grass species:	**?**	**0,21**	**0,24**
Number of species:	**?**	**13**	**11**
Number of obligate perennial species:	**?**	**4**	**1**
Number of grass species:	**?**	**3**	**5**
Number of geophytic species:	**?**	**3**	**0**
Number of annual species:	**?**	**3**	**5**

recovered after the drought (sites no. 9, 7, 5, 10, for details, see SOM). A segmented regression analysis identified three break points for trends in scorpionstail cover based on AICc for the years 2014, 2016 and 2021 (Fig. 8). The fit of the segmented regression shows how the cover of the *Brownanthus pseudoschlichtianus* population responds to the extreme drought. The year 2014, with a rainfall of 84 mm (close to the average of 89 mm), was the last year with scorpionstail mass flowering and formation of side branches. In 2015 (49 mm), 2016 (60 mm), and 2017 (18 mm), many plants died, while others still survived with a few side branches. The lowest level was reached in 2018 and 2019, i.e. four to five years after the last sufficient rain year. Only ten years after 2015, the remaining dead canopy fragments also started to disappear (see site no. 4 in Fig. SOM 45). The recovery process had a lag phase of one to two years after the first sufficient rain in 2020 (79 mm) because seedlings first had to germinate in protected safe sites and show a proper growth rate of the cover only by 2022. In numerous sites (site no. 3, 12,14, 35, 41, 42,43, see SOM) the cover of scorpionstail kept increasing through 2024 and the recovery process will likely continue for another few years, given sufficient precipitation.

3.2.3. *Changes prior to the centennial drought*

While the course of the decline and recovery during and after the recent drought is well reflected by the changing cover or presence/absence of *Brownanthus pseudoschlichtianus* during the last 10 years, the change over a longer period of time prior to the recent drought is less easily captured.

However, in 23 of our 59 study sites, the change in cover of scorpionstail since before 2014 was recorded (Fig. 9). Only two sites (shown in grass green colour, located in the mountains, associated with higher moisture) showed increased cover and only two other sites retained the same percent cover. The other 19 study sites with data from before 2014 did not show dead remains of *Brownanthus pseudoschlichtianus*. Therefore, we know for sure that the scorpionstail population was not killed by the centennial drought but must have been lost before the early record date and 2015. All long-term monitoring sites (see for example site no. 9 in Fig. 7) showed that there had not been a major drought during

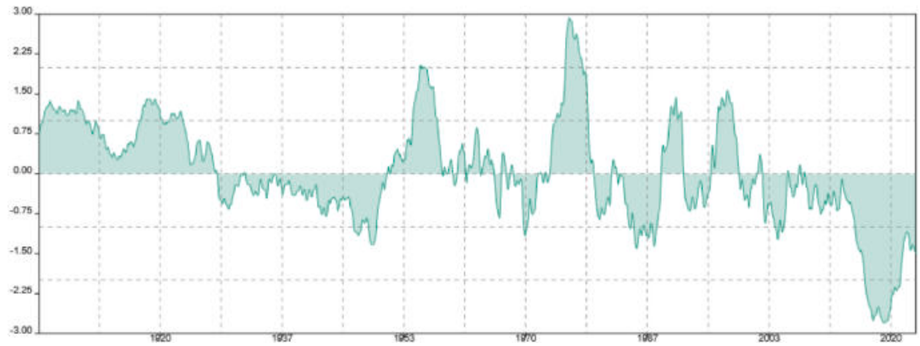

Fig. 6. Modelled SPEI values at Numees, in the Richtersveld National Park, covering the time from January 1902 until the end of 2023, calculated for the scale of 36 months. Y-axis = SPEI (Beguería et al., 2010), values below zero indicate the severity of drought. X-axis = years from 1902 to 2023. The recent drought is the longest and the most severe drought since January 1902. Data source: SPEIbase v.2.10 (Beguería et al., 2010).

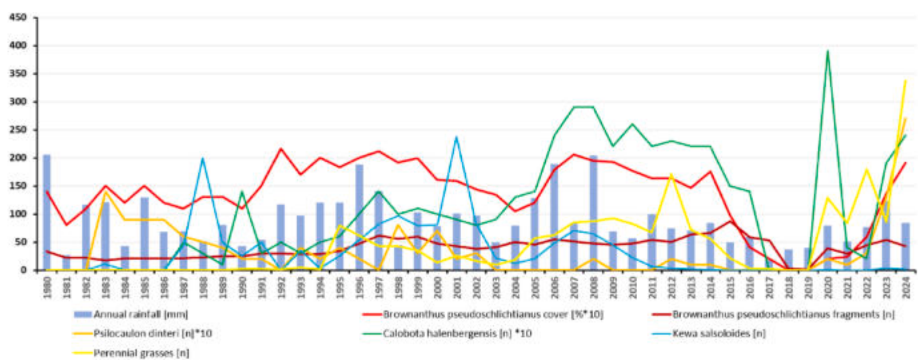

Fig. 7. Monitoring site no. 9 at Numees from 1980 to 2024, timelines of important taxa and life forms. Note the increase of grasses and *Psilocaulon dinteri*, after the drought.

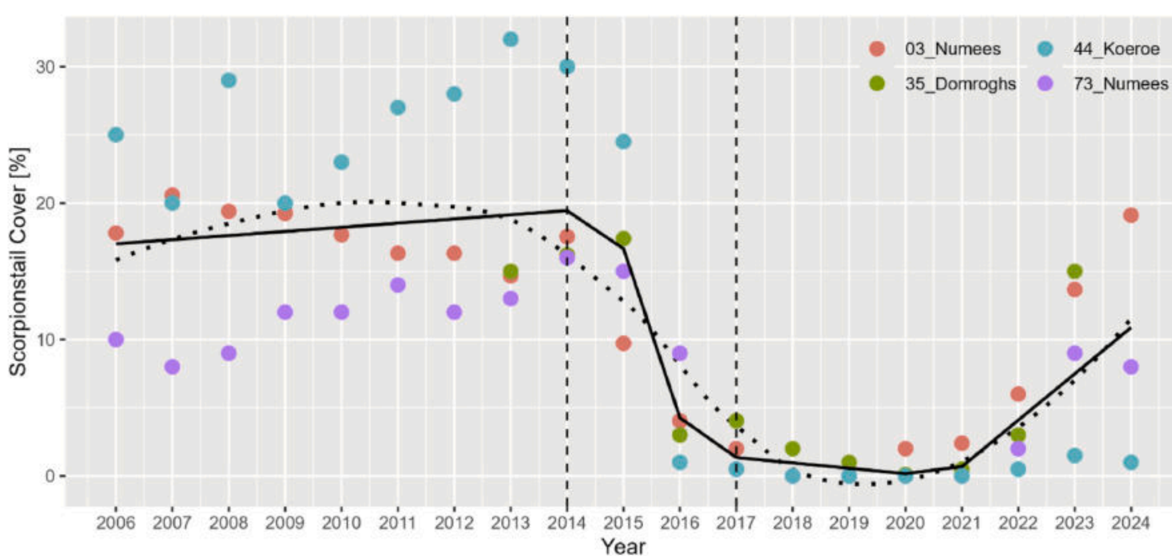

Fig. 8. Development of scorpionstail percentage cover during the monitoring period on four permanent monitoring plots. The dotted line represents a loess smoother showing the overall trend, while the solid line represents the fit of a segmented regression model with three breakpoints. Vertical dashed lines bracket the time interval of major decline in scorpionstail cover.

that period of time. The overwhelming majority of the sites thus provided evidence for the hypothesis that there had already been a widespread degradation of scorpionshrubland before the recent drought caused by reasons other than drought.

Sadly, a longer dimension of a slow decline of plant species richness is also recorded in protected areas within the Richtersveld National Park (Van Wyk et al., 2024) and in the Richtersveld mountains, in spite of their relatively higher precipitation and higher resilience of the vegetation: A comparison of the flora of one square kilometre in the valley of Numees also reveals the loss of many species (Jürgens and van Wyk, personal observations).

The observed spatial dimension of desertification in the Richtersveld will be globally outstanding if this trend will not be reversed due to higher precipitation within the coming years. A similar dimension of

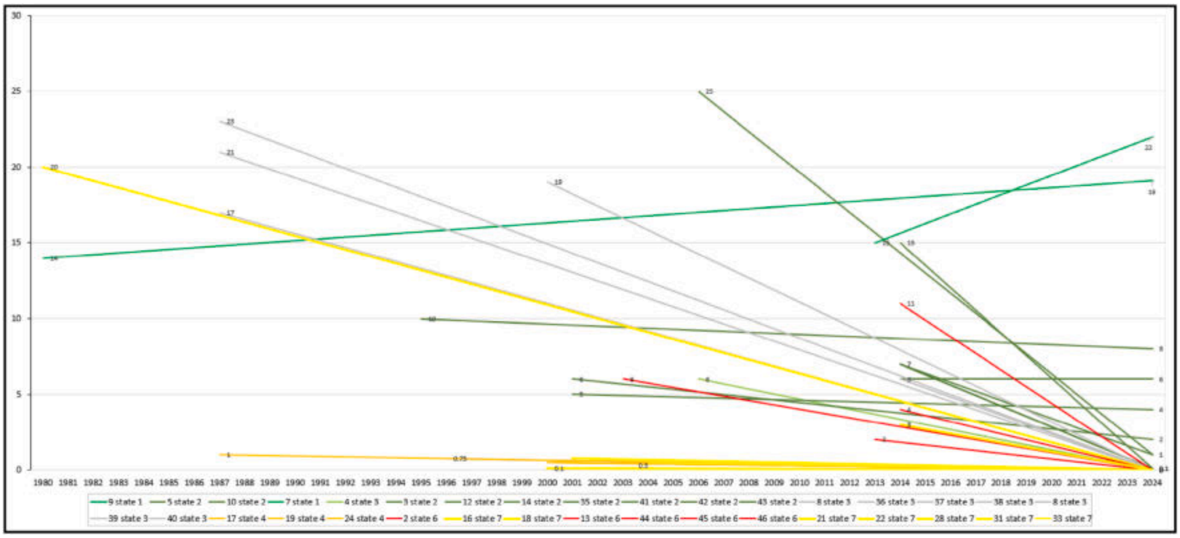

Fig. 9. Change of cover of *Brownanthus pseudoschlichtianus* in the Richtersveld looking back beyond the present drought. Note that only the two study sites with resilient scorpionshrubland showed an increase while only two sites retained more or less the same percent cover. (Note: For site no. 18 the year 1914 was graphically depicted as starting in 1980).

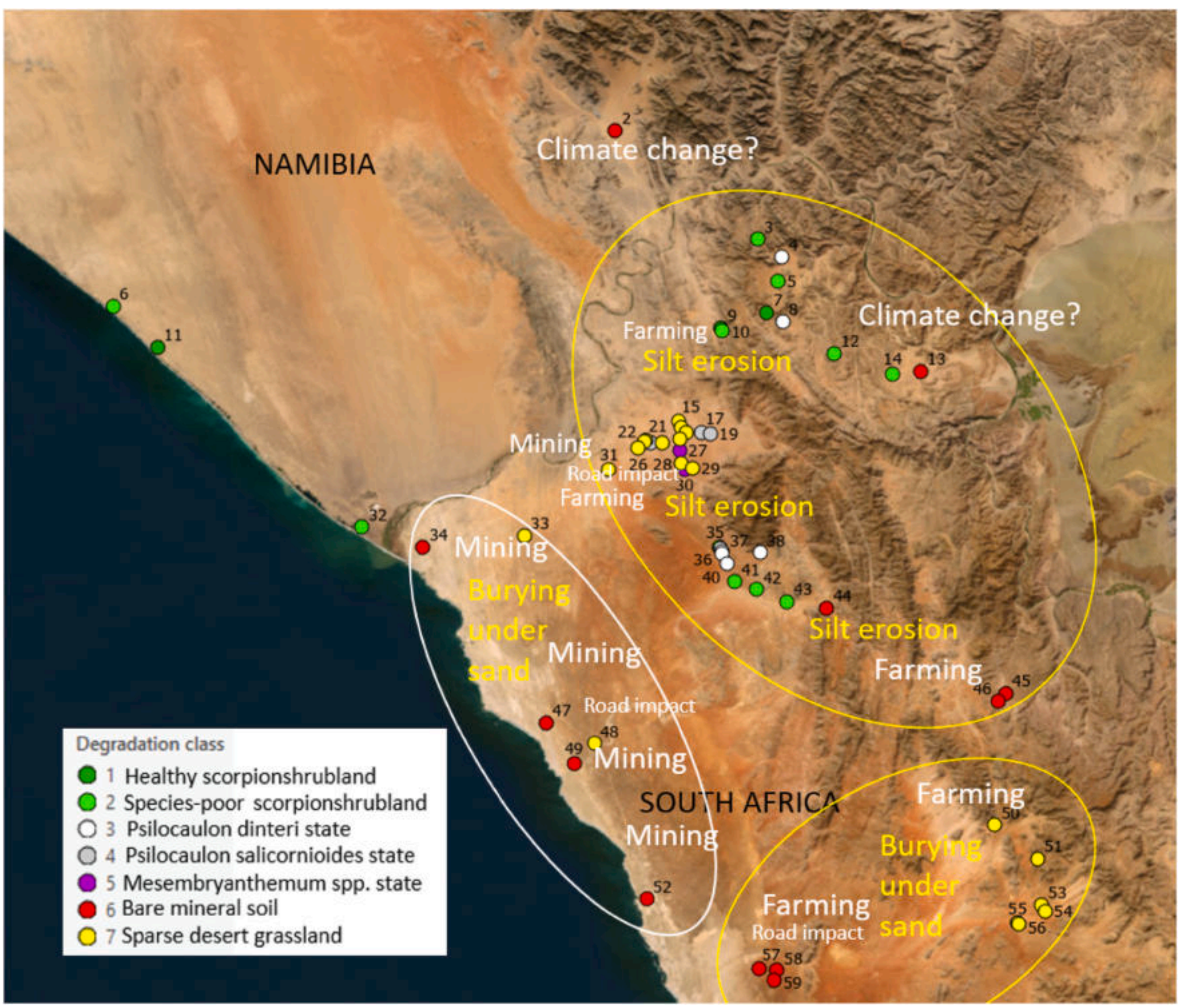

Fig. 10. Distribution of study sites and degradation states. Oval outlines circumscribe regions where the two most important processes of ecosystem change are dominant, highlighted by text in yellow colour. Spatial hotspots of the role of drivers are shown by text in white colour. Source of satellite image provided by ESRI Arc GIS Pro: Earthstar Geographics. Note that only a few sites in the Richtersveld National Park and in Namibia are interpreted as habitats without any major anthropogenic impact and assumed as being degraded due to climate change. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

change along a desert margin would be comparable only to the waxing and waning of the Sahara Desert and the complementary retraction and expansion of Sahel rainfall (Thomas and Nigam, 2018) which is not supported by the most recent studies of global desert expansion trends. Wang et al. (2022) review recent advances and uncertainties in the observation and prediction of dryland productivity, while Wu et al., 2023 report that the majority of deserts around the globe did not show expanding trends from 2000 to 2019, with the exception of smaller areas in Tunisia, Tajikistan, and Peru. With regard to the Namib Desert, Qiao and Wang (2022) studied the greening trends and their causation in the Namib Sand Sea over 2000 to 2012, mainly driven by precipitation.

3.3. *Processes of degradation and their spatial distribution*

The states of degradation, introduced in 3.1. are unevenly distributed within the study area. Here, we discuss the present spatial distribution of both, the states 1 to 7 and the degradation sequences I to IV, illustrated as a map in Figs. 2 and 10.

The study sites with species-rich and species-poor remaining scorpionshrubland (green circles) were clearly limited to the two moister habitat types. The northern study sites were all located in plains and valleys within the mountains of the Richtersveld National Park. The central group of study sites were located in front of the Ploughberg and received higher rainfall due to orographic air lifting.

The degradation states 3 and 4 (white and grey circles), dominated by *Psilocaulon* species, were only recorded in the northern and central parts of the Richtersveld, and were missing in the very sandy areas and near the coast.

Bare soil (red circles), the most degraded state of (former) Succulent Karoo vegetation, was found in two very different regions. Four sites (site no. 2, 13, 45, 46) were close to the Orange River and/or eastern boundary of the occurrence of *Brownanthus pseudoschlichtianus* (and the Succulent Karoo), at the margin to the East Gariep Centre of the Nama Karoo Biome. One site (44) is located in the easternmost part of the plain south of the Ploughberg. The other sites are grouped together within the coastal sand sheets where aeolian sand had buried vegetation, as indicated by the sequence type IV.

The strongest deviations from the original scorpionshrubland and from the Succulent Karoo in general were found in the sparse desert grasslands of the study sites of degradation state 7 (yellow circles). As shown in Figs. 2 and 10, this state is observed in two quite different landscapes of the Richtersveld. On one hand side there are vast plains inundated by aeolian sand in the southeastern Richtersveld. On the other hand, this state is also abundantly found in a broad band south of the Orange River from near Alexander Bay to the Annisvlakte. In the landscapes of the Richtersveld the degradation state 7 is associated with quite different ecosystem processes. This insight calls for a closer look at the processes, mechanisms and feedbacks which accompany both, stability and desertification in drylands (Ogle and Reynolds, 2004; Ravi et al., 2010). In the following we will first unpack more detailed observations on the more northern accumulation of state 7 sites, followed by a closer look at the southeastern hotspot of state 7 sites.

3.3.1. *Silt erosion in the northern Richtersveld*

The northern group of state 7 sites is found from east of Alexander Bay to the Annisvlakte, south of the boundary separating Desert Biome from Succulent Karoo Biome (Fig. 2). Some of these sites (17, 24, 2, 15, 16, 18, 20, 31) were inhabited by the tall stem succulent shrub *Euphorbia gummifera*, which occurs in huge populations in the Southern Namib Desert, north of the Orange River. All these northern study sites of state 7 were characterized by signs of extreme wind speed with aeolian erosion and transport of sand and silt. Earlier habitats of scorpionshrubland were now characterized by topsoils of pure sand with proportions of gravel, forming large ripples. Plants showed damage from abrasion due to sandblasting. Two sites (22 and 23) were identified as source points of dust storms (Heleen Vos, University of Stellenbosch, pers.comm.). During strong bergwinds, satellite images show the eroded silt as linear dust bands reaching over a hundred kilometres over the Atlantic Ocean (Fig. 11).

In silty soil landscapes stability of intact Succulent Karoo ecosystems and their vegetation is partly depending on the diversity of plant growth forms (Jürgens, 1990) which, among other processes, facilitate sedimentation and accretion of aeolian transported silt (Gröngröft et al., 2015; McAuliffe et al., 2018; McAuliffe, 2022). Silt sedimentation is enhanced within the dense sheltered cushion-like dwarf shrubs of *Brownanthus pseudoschlichtianus*. Over long periods of time, these ecosystem engineers accumulate enough silt to form silty plains (Fig. 3.1), which we interpret as a desert loess deposit (Lancaster, 2020).

An important property of the silty topsoils of scorpionshrubland is the relative stability against wind erosion. After loss of the vegetation cover a polished soil surface remains stable, when no disturbance by stock or game occurs. Silty soils in this initial erosion state are further stabilized by remaining roots and fixed plant detritus, sometimes by biological surface crusts.

Temporary protection of a stable soil surface is also provided by the remains of the canopy of dead plants, which can stay for another decade until they decay completely. The remains of dead dwarf shrubs on the silty topsoil also provide special conditions for the soil water balance. In addition to the rain, the combed-out fog moisture adds to the plant-available water. The combed-out water and the frequent small amounts of rain are stored in the upper topsoil and provide a basis for the germination and growth of succulent plants with low rooting depth (February et al., 2013; Francis et al., 2007).

However, this stability is immediately lost when trampling by stock (Hendricks et al., 2005) or sandblasting, resulting from aeolian sand transport from the upwind area, occur, which both initiate further silt erosion. The aeolian losses of silt cause a relative increase of the residual heavier sand grains. The resulting transformation of a silty into a sandy topsoil has severe consequences for the ecology and for plants. A sandy topsoil is not as stable as silt, and the movement of sand grains at the surface causes abrasion of plant surfaces and impedes germination and establishment of new plants. Aeolian transport of sand and gravel causes even stronger mechanical destruction of plant surfaces and the formation of ripples at the soil surface. The formation of biological surface crusts is inhibited or impossible. Rainfall infiltrates deeper into the soil, thus increasing competition with plants that have deeper roots.

When these topsoils are turned into a sandy, single-grain structure, the habitat changes to the extent that the former pool of species can no longer persist, and a new pool of species invades the site, partly coming from sandy patches in the original landscape, partly invading from

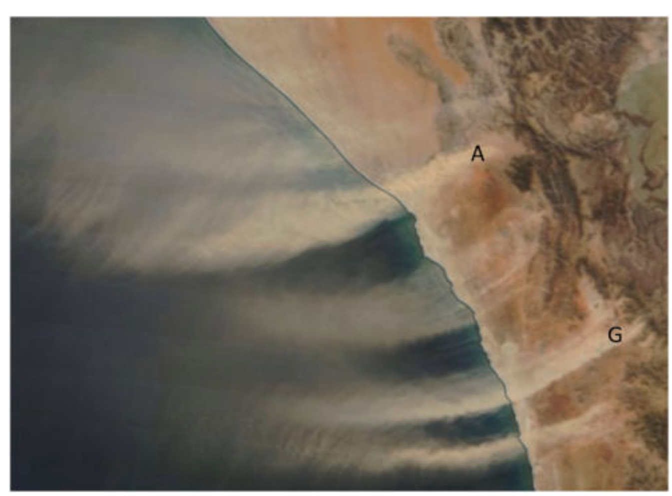

Fig. 11. NASA Worldview August 30, 2022. Note the strongest aeolian dust export during strong easterly bergwinds from the Annisvlakte (A) and in the Grasvlakte (G).

distant landscapes. The sandy topsoil associated with sand-blasting favours the establishment of desert grasses. The sandy habitat is no longer suited for *Brownanthus pseudoschlichtianus* which is adapted to silty soils (Jürgens, 1986, 2004; Jürgens et al., 2006; Nussbaum, 2003).

Due to the altered topsoil, the shift from Succulent Karoo vegetation to sparse grasslands, typical for the Desert Biome in the Southern Namib, oscillating with bare soil in dry years and some annuals in moist years, may be irreversible. Until early 2025, no study site which degraded to state 7 recovered to state 1 to 4. However, after good winter rain we observed the return to state 5 (annual vegetation dominated by *Mesembryanthemum* species), but there is no site that has developed from state 5 to states 1 to 4. We cannot exclude that an uninterrupted series of several years with good winter rains might allow a reverse development turning state 5 into any of the states 1 to 4. However, such a process has not yet been observed.

So far, the observed events of good rainfall resulted in mass germination of annuals and biennials, including the more opportunistic species of *Mesembryanthemum* (state of degradation 5). While the living and even the dead standing biomass of these species shelter the soil surface against aeolian erosion for several months up to a year, these species degrade the habitat by their ability to take up soluble salts with their root system (De Villiers et al., 1995). After death and decomposition, these plants release the accumulated salt, making the habitat inhabitable for plant species not adapted to higher topsoil salinity (Vivrette and Muller, 1977).

In summary, these changes in soil properties facilitate the shift from a species-rich, stable and productive dwarf shrub vegetation of the Succulent Karoo to a species-poor, unstable and less productive grassy Desert vegetation. Also, the substrate and the geomorphology are altered. Therefore, we propose to regard these changes as a southward extension of the margin of the Namib Desert.

3.3.2. *Sand burying in the southern and western Richtersveld*

In the southern group of study sites, which were also turned from scorpionshrubland into sparse desert grassland, we observed a very different process, which triggered the degradation sequence III: Here, easterly winds transported large masses of aeolian sand, which buried and killed the former scorpionshrubland. The process observed in sequence III is similar to sequence IV.

As observed in silty ecosystems, certain plant growth forms also buffer and mitigate potentially dangerous transport of aeolian sand. Huge volumes of sand are immobilised for years, decades or centuries due to the formation of phytogenic nebkhas, however these sand masses are released and mobilized by the dissolution of nebkhas, following death of the plant (Hesp and Smyth, 2017; Mayaud and Webb, 2017).

These stabilizing properties of intact Succulent Karoo vegetation are gradually lost, when thinning of the standing biomass of the perennial dwarf shrub vegetation takes place. Such a loss of biomass and cover in terms of density and size of plants can result from drought, erosion, heat, grazing, trampling, abrasion due to sandblasting, or burying of the plants under mobile sand (Ogle and Reynolds, 2004; Ravi et al., 2010; Henschel and Jürgens, 2024; Jürgens, 1996).

The thinning of the vegetation causes higher wind speed at the soil surface resulting in wind erosion and aeolian transport of both, sand as well as silt. The transport of sand and silt again causes cascading effects and negative feedbacks. Aeolian sand transport causes damage or even death of plants because of sand-blasting abrasion (Jürgens, 1996) or burying plants under mobile sand. Dust causes less abrasion, but – if deposited on plant surfaces – the contamination reduces plant metabolism due to blocking stomata and reducing light infiltration through the leaf surface (Turner, 2013), especially observed in species which have a papillate rough epidermis (personal observation P. van Wyk).

The mobilisation of sand also includes several phases and cascading effects. Even a slight thinning of the plant cover immediately allows increased transport of sand, because the wind speed is less reduced by plant structures. A much larger volume of sand gets mobilized when nebkha generating plants die and, after a lag phase of up to ten years, decay and the accumulated sand in their wind shadow becomes airborne (Hesp and Smyth, 2017).

Despite the loss of the silt component in the soil, in some instances, especially in the moister southern Richtersveld, vegetation which was buried under mobile sand plumes, could recover once the cause of the mobilisation of sand (stock posts, mining trenches, road works) is stopped. Some of the time series (for example, see Fig. 12) indicate that the vegetation may have recovered after being buried under historical sand plumes, at least partly. Similarly, the farm name Grasvlakte (meaning "grassy plain") indicates that grassland previously occurred.

3.4. *Role of different drivers*

In the following we present evidence for some obvious anthropogenic drivers, followed by a discussion of the potential impact of climate change.

3.4.1. *Anthropogenic drivers of localized impacts*

Numerous study sites (see Tab. SOM 55) provided direct evidence for the role of (a) **mining infrastructures**, especially active and abandoned quarries and prospecting trenches. A second group of sites clearly showed the impact of (b) **roads**, including simple, often-used tracks in sandy areas or modern tar roads. At other sites, the degradation was directly related to (c) **farming activities** (grazing and trampling around stock posts, wind pumps and settlements).

These three drivers had in common that they **locally** degraded or removed the vegetation and thereby triggered either the erosion of silt and/or the mobilisation of aeolian sand transport, associated with abrasion and the formation of sand plumes. In addition to aeolian transport of sand, dust also damaged and killed plants, as observed along roads.

3.4.1.1. Mining. The infrastructure associated with the mining industry was easy to identify on satellite imagery (e.g., see examples in the SOM: site no. 49, 52, 47, 34). These images showed the long-lasting impacts of historical mining, including open pits and trenches, the deposits of overburden and tailings, and the apparent lack of adequate rehabilitation measures. We observed a substantial increase in the number of mines and their cumulative surface area during the last decade. As an example of the effects of mining, we show the time series at study site 49 near the Holgat mouth. Open mine trenches allowed wind erosion and sand mobilisation and the development of a dune plume, which expanded exponentially, burying vegetation in its path (Fig. SOM 87, Tab. SOM 33).

3.4.1.2. Roads. During road construction, sand and silt were almost always mobilized, causing problems. Along gravel roads, these impacts persist during the lifetime of the road. Examples of the local impact on the nearby scorpionshrubland are given in the SOM (sites 48, 57 and 58).

3.4.1.3. Farming. The effect of small stock grazing near stock posts, wind pumps and settlements was evident in time series of satellite images. Our first example is presented in Fig. SOM 93. At study site 59, located east of Port Nolloth, a small bare area without vegetation in a 100 m radius around a fenced stock post was seen in 2004. This triggered massive growth of annual *Mesembryanthemum* sp., visible as blackish colour in 2006. During the drought, the vulnerable bare soil surface caused aeolian sand transport by the predominant southerly wind. The sandblasting caused further abrasion and further degradation of vegetation further away, causing more aeolian sand transport. Meanwhile (2023), due to the cascading effects, the front of the sand plume buried vegetation 615m north of the stock post. Similar effects were visible in numerous places, especially in the lowlands of the Richtersveld, the so-

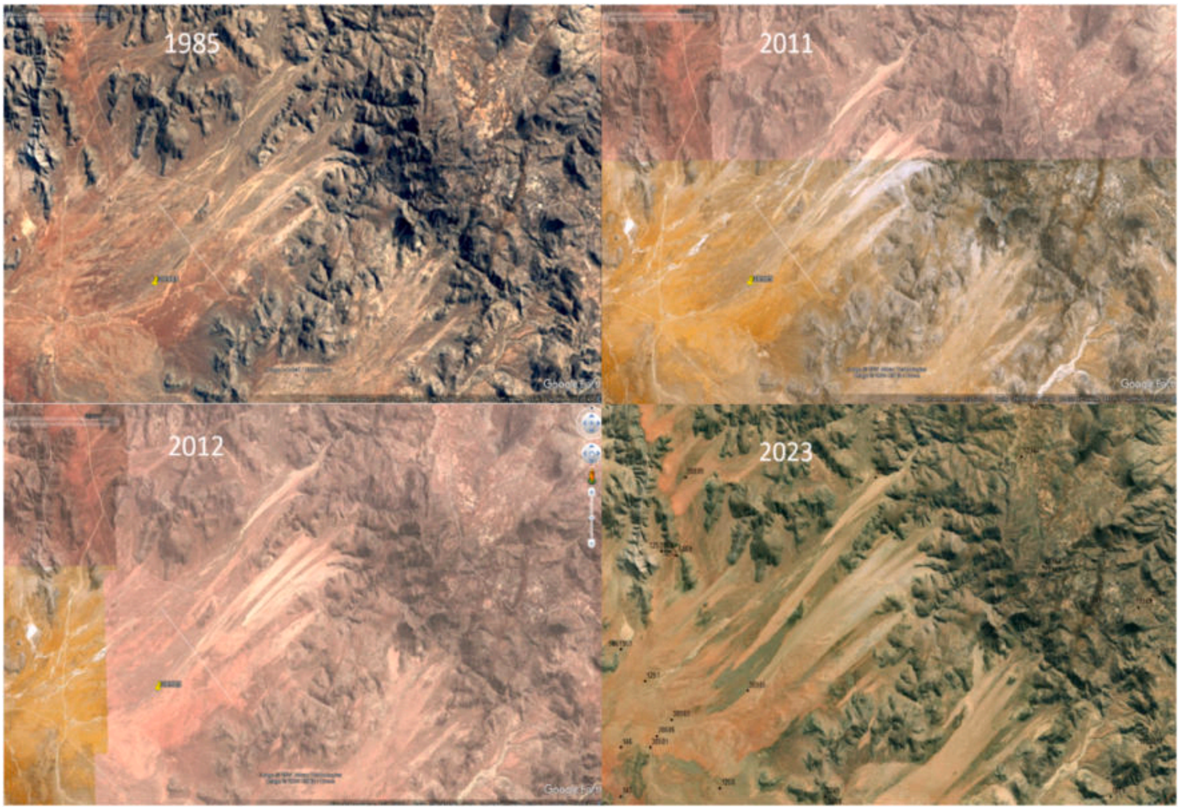

Fig. 12. Satellite images show the expansion of sand plumes, starting with initial small plumes next to river beds in 1985 and expanding strongly during the subsequent years, especially during the recent drought (Image credits Google Earth, Maxar Technologies, Landsat/Copernicus, CNES Airbus.

called Sandveld (see sites 50 to 56 in the SOM).

A special situation was observed in the escarpment apron in the southern Richtersveld, at the farm Grasvlakte (see Fig. SOM 147 and following three and Fig. 12) and adjacent farms. Here, sand plumes were generated near stock posts and wind pumps (see site 51 in SOM) in the plain at ca. 350 m asl. This "in-situ caused" degradation was intensified and expanded by imported allochthonous sand originating from the escarpment at altitudes up to 1000 m asl., where overgrazing and ploughing triggered sheet erosion across a distance of 15 km (Fig. 12). The mass transport of sediments down the escarpment in steep river valleys and the deposition of the allochthonous sand in sediment fans (Figs. 12 and 13), exposed to strong bergwinds (foehn storms) from the east should be regarded as a specific vulnerability of that entire landscape setting. The combined effect of two sand sources and the geomorphological vulnerability caused the largest and the most rapidly expanding sand inundation recorded in the entire area.

We propose that a major part of the more than 30.000 ha of the wider Annisvlakte in the northern Richtersveld was covered by healthy scorpionshrubland during historical times. The historical photograph of site 18, taken in 1914 (Fig. 5.1), shows dense scorpionshrubland 111 years ago at a site where already in the year 2003 no more *Brownanthus pseudoschlichtianus* was present (Fig. 5.2). This hypothesis is also supported by numerous historical vegetation records, which prove the presence of *Brownanthus pseudoschlichtianus* and other species typical for healthy scorpionshrubland in the Annisvlakte and Goariepvlakte during the 1980s and 1990s (see our historical sites 36, 37, 38, 17, 27, 15 in the online material). Our relevés from the 2000s show that severe degradation occurred well before 2003.

It is likely that historical grazing and trampling impact from the settlements Annisfontein and !Khubus caused degradation and a change of vegetation and ecosystem properties. Already in June 1989, older people at !Khubus reported that there had been more bushes in the Annisvlakte in the past. During the search for the position of the historical photo from 1914, we found the historical ox wagon trail that still forms a linear depression. This and various artefacts along the trail indicate that this was a well-travelled route accompanied by grazing and trampling of the vegetation. Therefore, it is likely that the degradation process with loss of plant cover, loss of the silt component of the topsoil, and sand mobilisation by the wind started well before the drought impacts became evident.

The increase of aeolian sand movement buried parts of the landscape in and adjacent to the Annisvlakte, including the famous Cornellskop with vulnerable populations of the tall *Aloidendron pillansii* (Duncan et al., 2005) and the tiny *Crassula corallina*. Still observed in 2015 by P. van Wyk, the population of *C. corallina* became extinct in 2017.

In summary, localized impacts from farming, mining activities or road construction are very obvious initial triggers that, coupled with strong winds, generate a sand plume expanding over decades and destroying large surface areas. There are likely several hundred such localized source points in the Richtersveld, which should be identified in future studies accompanied by remote sensing studies to quantify dust plumes thereby flagging sources of eroding topsoil silt.

3.4.1.4. Diffuse anthropogenic degradation in the wider landscape. In addition to the localized sources of sand plumes, all the above-mentioned land uses have a diffuse effect on the vegetation in the wider landscapes. Even if sand plumes show clear limits in the satellite image, aeolian transport of sand and dust with its abrasive impacts goes far beyond the visible sediment boundary and may impact a plume of tens of kilometres length.

The extreme degradation of Succulent Karoo vegetation has been abundantly shown in the somewhat more humid Namaqualand (Hoffman et al., 1999), where also fence line contrasts are ubiquitous and make the effect of different grazing practices visible (Todd and Hoffman, 1999).

Even in the fenceless Richtersveld, livestock grazing and trampling

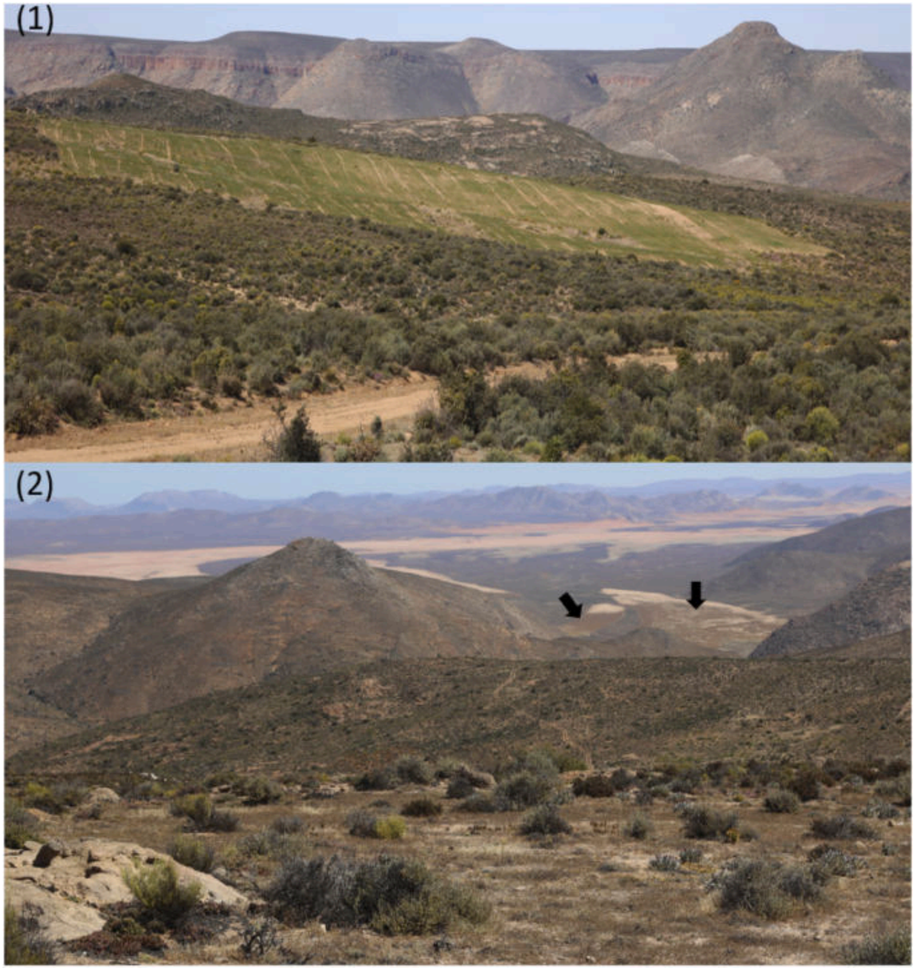

Fig. 13. The sources of the sand invasion in the Grasvlakte plain are partly located in the Kosies plateau above the escarpment. (1): Ploughed fields on slopes generated sheet erosion (October 01, 2024). (2) Degraded vegetation in the Kosies area, at 901 m altitude, i.e. more than 500 m above and 15 km northeast of the farm Grasvlakte, looking westwards on the sand-covered landscapes of the farm Grasvlakte, indicated by the bright colour. Note that the sand plume closest to the escarpment was partly covered by dead Mesembryanthemum barklyi plants (brownish colour, indicated by black arrows), probably caused by higher precipitation (October 01, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

have an impact on the wider landscape beyond the shown cases of stock posts and areas severely trampled by cattle, which led to the formation of sand plumes. These wider impacts of grazing and trampling become visible by the typical remaining stumps of heavily eaten plants and the encroachment of less edible species like *Galenia africana, Psilocaulon salicornioides* and spiny *Asparagus* species. Hendricks et al. (2005) consider a 2.5 km "grazing orbit" around stock posts and they show an increase in number of species and palatable species up to 1 km away from a stock post. Compared to nearby unfenced plots, experimental fenced plots (Fig. SOM 10) show measurable differences, though weak in terms of biomass.

3.4.2. The role of climate change

A strong argument supporting an outstanding role of mining and farming as contributing to the degradation in the entire Richtersveld is the comparison of the Richtersveld with the Tsau//Khaeb (Sperrgebiet) National Park (TKNP), positioned directly adjacent north of the Orange River. Despite higher aridity and even stronger winds, no such degradation has been reported for most of the TKNP, except for stretches along the Orange River. Since the declaration of the Diamond Sperrgebiet in 1908, no farming, mining or other human activity has taken place outside the diamond mining infrastructures, except for emergency grazing during drought years in the 1960s to early 1980s. However, the TKNP is not exempted from global climate change. Therefore, we conclude that climate change alone has not (yet) caused a measurable extent of degradation of the scorpionshrubland in the TKNP. In fact, in 2024, even in the more arid and stormy parts in the northern part of the TKNP, healthy scorpionshrubland communities were observed and recorded (site no. 1), including a number of other plant species which typically formed part of the scorpionshrubland in the Richtersveld. Similarly, also scorpionshrubland in the mountains of the TKNP is in good condition.

Also in the Richtersveld, a few of our study sites are considered to be controlled only by effects of climate change, because they are not exposed to anthropogenic impact. These are very arid sites with sparse vegetation in the eastern Richtersveld National Park (e.g. 13, 12, 14) and site 2 in Namibia (outside TKNP), where no more farming has taken place since the late 1970's. In these sites, large populations of entirely dead *Brownanthus pseudoschlichtianus* plants do not show any sign of grazing or trampling. We interpret these cases of vegetation collapse as caused by the centennial drought which we regard as driven by climate change.

Based on our observations, the most important climatic changes that drive vegetation degradation are related to a) heat, b) lack of precipitation during severe drought periods with decreased available soil moisture, c) higher evapotranspiration due to higher temperatures and d) increased exposure to strong winds. The effects of increased heat and wind exposure are discussed below in more detail.

3.4.2.1. Heat. We observed that during the past decades, an increasing number of succulent plant species with very large succulent leaves, like *Cheiridopsis, Dracophilus* or *Hartmanthus*, show strong dieback, especially in the hotter and generally more degraded Orange River Valley. One hypothetical explanation for this pattern could be that parts of the Richtersveld, especially at low altitudes in the Orange River Valley, may have already shifted outside the temperature niche of Succulent Karoo plants.

This hypothesis is supported by the observation that numerous plants in the nursery of the Richtersveld Desert Botanical Garden die when air temperature exceeds 38 °C during the growth season, even when cultivated under shade nets (personal observation PvW). Already in 2003, monitored populations of *Aloidendron dichotomum* were in poor condition (Foden et al., 2007). Twenty years later, in 2023, one of five populations in the Orange River Valley showed 60–75 % mortality, and the other four even 75–90 % mortality (Wendy Foden, personal communication in March 2025). The authors also regard the drastic declines of *Pachypodium namaquanum*, *Aloidendron pillansii* (Duncan et al., 2005), *Crassothonna opima* and *Tylecodon paniculatus* as at least partly caused by heat waves.

The flora of the Succulent Karoo Biome in the Gariep region and the southern Namib Desert is generally adapted to milder temperatures compared with the Nama Karoo. The long extension of the Succulent Karoo flora in a narrow coastal strip into the central and northern Namib (Jürgens, 1991, 1997) shows that the combination of mild temperatures and high air humidity forms an important element in the environmental envelope, even compensating for the winter rainfall seasonality. Musil et al. (2004) showed in an experimental approach that the current thermal regimes are likely to be closely proximate to tolerable extremes for many endemic succulents in the region and that anthropogenic warming could significantly exceed their thermal thresholds. In fact, the increase of temperature in 2024 reached 1.5 °C in South Africa and 1.6 °C in Namibia, compared to the 1951 to 1980 averages (BerkeleyEarth, https://berkeleyearth.org/). See also ECMWF (Copernicus Climate Change and Atmosphere Monitoring Services, 2025), also made available by Meteoblue (2025)). Therefore, it is likely that highly susceptible leaf succulent species show a dieback following heat waves in the hottest environment of the southern Namib, namely, the Orange River valley. The most recent publication on future climate change by Engelbrecht et al. (2024) presents projections of further increasing heat and decreasing soil moisture availability.

3.4.2.2. Wind. Strong winds are an important direct driver of ecosystem processes in the study area. Kestel et al. (2023) present the Namib Desert as the most wind-erosion-prone strip of southern Africa. However, the high vulnerability of the Succulent Karoo in the southern Namib was not identified, probably due to the low vegetation signal in remote sensing images. We did not find a recent study of changes in the wind system of the region. However, global warming increases the temperatures above the western parts of the subcontinent (Engelbrecht et al., 2024) faster than the ocean. Therefore, it may be possible that wind speed and frequency of strong winds and the inevitable associated damages will increase along the coastal region.

In this context, it is important for the future environment in Namibia that aeolian sand transport across the Orange River should not increase. Prior to the construction of the Gariep Dam (built 1972) and Vanderkloof Dam (built 1977), the flooding of the Orange River was mostly annual but sometimes ephemeral (personal communication with elder citizens of Alexander Bay). The river dried up completely from 1963 to 1964 and 1972 to 1973. With ongoing climate change, sand transport across the riverbed into Namibia may increase again.

3.5. Conservation, adaptation and mitigation

The degradation and the observed cascading processes threaten biodiversity, ecosystem functions and services, farmland and human infrastructures, in the Richtersveld, but also in adjacent parts of Namibia. A diversity of measures will be necessary to mitigate the threats or adapt to the impacts of these four sectors. It is beyond the scope of this article to derive detailed proposals for concrete conservation and restoration strategies. A separate publication shall distinguish and map the vulnerability of different ecosystems and derive strategies for practical measures.

The relative intactness of the vegetation in the neighbouring and more arid last remaining wilderness of the Tsau//Khaeb National Park indicates the potential of recovery in the more strongly used Richtersveld if mining and farming would introduce a set of management and restoration principles. In practical terms the focus of adaptations must seek to avoid and reduce conditions which trigger mobilisation of sand or dust. Only a few recommendations shall be derived from the results of our study:

- Restore existing damage immediately by applying ecological restoration projects.
- Stop sand and dust transport in the landscape by establishing efficient sand trapping and fixing structures in strategic positions.
- Fill existing trenches and quarries and cover them with tailings and gravel.
- For techniques, make use of scientific support networks like the World Overview of Conservation Approaches and Technologies (WOCAT).
- For future economic activities: Implement and enforce rules which avoid new environmental damage.
- Execute mining operations only when aeolian transport suppressing measures are applied.
- Sustainable farming methods should be implemented and seasonally adapted to ensure sufficient vegetation remains to prevent wind erosion.

More generally, we recommend stronger efforts and investments into the conservation of this extraordinary hotspot of biodiversity. Conservation should focus on approaches that reduce habitat degradation and species extinction, including updating red lists and ex situ conservation. Existing laws need to be enforced. The authors will strive to improve and intensify the monitoring in cooperation with the relevant institutions.

Adaptations to climate change are far more difficult. Protection of the rich biodiversity of the Succulent Karoo will require new strategies and new networks of protected areas, including ecosystems at higher altitudes in the Richtersveld mountains and in the mountain ranges east and north of Rosh Pinah, as a potential refuge for species adapted to mild temperatures, in a hotter and drier future. The presently planned projects for green energy production in South Africa and Namibia will help to decarbonise the global economy, in the long run. However, their industrial development could also cause large-scale additional local environmental stresses and damages and losses of biodiversity if the vulnerability of the ecosystems is insufficiently addressed. We recommend immediate trans-boundary measures to protect the ecosystems and the biodiversity in the entire Southern Namib region.

4. Conclusions

Our data show an unprecedented degradation of the scorpion-shrubland vegetation and the general flora in the Richtersveld region, affecting more than one million hectares of the northernmost Succulent Karoo in South Africa. Worst impacted are parts of the plains habitats where Succulent Karoo vegetation is locally replaced by bare mineral soils or sparse grassland. This change is accompanied by a decline of biodiversity, while new species from the Namib Desert enter the Richtersveld.

A large part of the decline has been caused by the recent unprecedented drought. However, our study sites provide evidence for degradation processes taking place during the last four decades. The comparison of a photographic document from 1914 (Fig. 5) with repeat photos since 2003 suggests that the healthy scorpionshrubland from 111 years ago must have vanished already long before 2003.

These changes are partly described as "desertification", i.e. mainly anthropogenic degradation of ecosystems and their productivity. Beyond the shown evidence for numerous cases of localized degradation caused by mining, roads and farming, we assume a general diffuse anthropogenic degradation in most of the Richtersveld. The important role of anthropogenic causation is strongly supported by the observation, that there is much less degradation of scorpionshrubland north of the Orange River, in the more arid Namibian Tsau//Khaeb (Sperrgebiet) National Park, which has largely escaped human occupation and farming until today.

However, the changes in the area between Alexander Bay and the Annisvlakte are best described as a southward expansion of the Namib Desert, because geomorphology, substrate, vegetation and flora changed accordingly.

With regard to the ecosystem processes which accompany desertification we identify the erosion and losses of silt and the cascading effects of transport and deposition of sand and dust, as two main processes which cause damage to both, nature and human infrastructure.

The interactive roles of anthropogenic desertification and the effects of climate change as projected by Midgley and Thuiller (2007, 2011) are difficult to disentangle. Based on our observations regarding effects of heat and wind, we propose that the various anthropogenic disturbances are the main drivers of disturbance, enhanced by climate change.

Therefore, stronger efforts and investments towards conservation and landscape management in this extraordinary hotspot of biodiversity at the edge of the Namib Desert, are needed. Restoration methods to combat the cascading processes caused by anthropogenic desertification need to be implemented and adapted to the specific ecosystems. Strategies how to adapt to climate change require further research and monitoring.

CRediT authorship contribution statement

Norbert Jürgens: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Antje Burke:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Pieter van Wyk:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Alexander Gröngröft:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Jens Oldeland:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaridenv.2025.105459.

Data availability

Data will be made available on request.

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