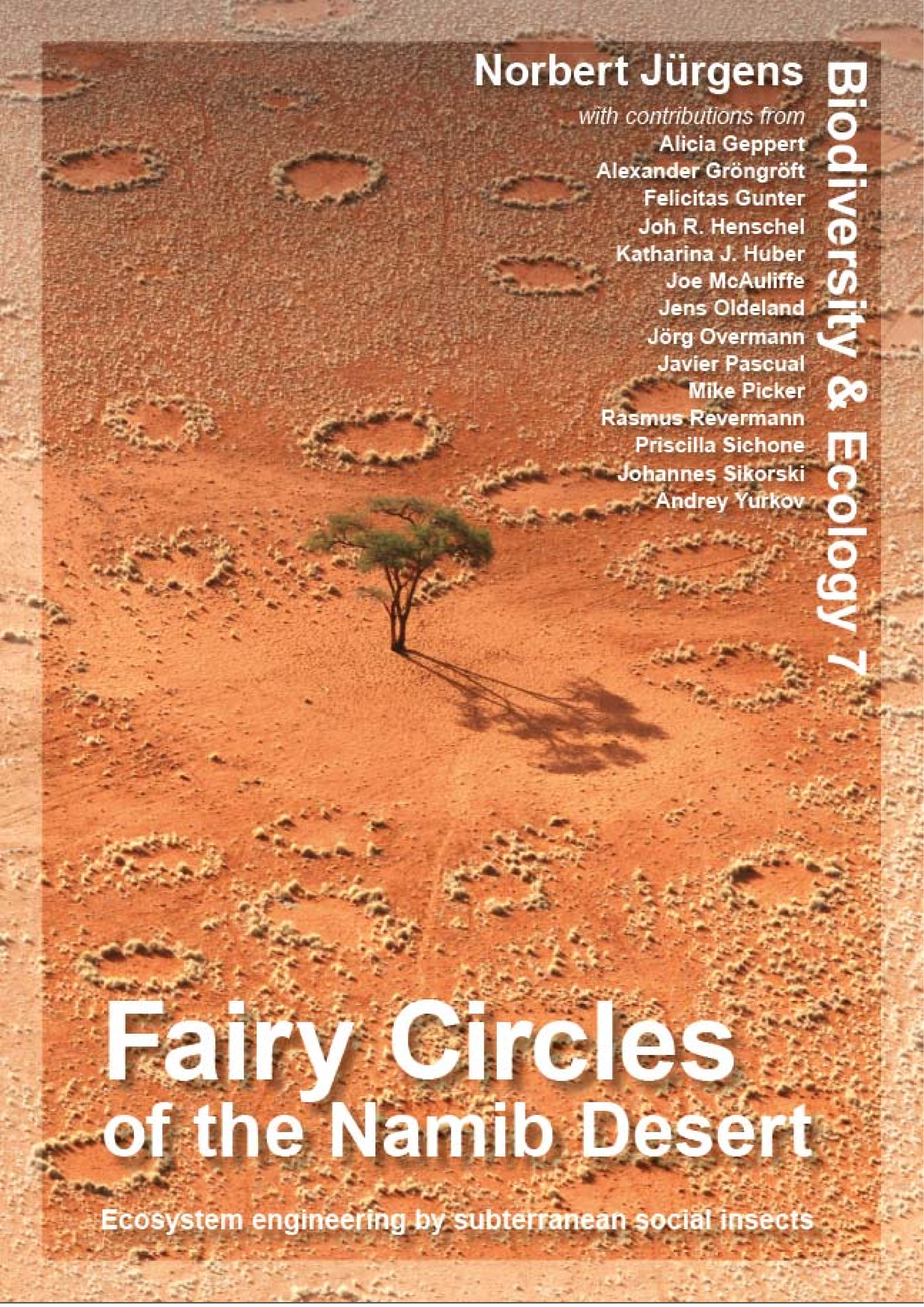

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Biodiversity & Ecology 7

Fairy Circles of the Namib Desert

Ecosystem engineering by subterranean social insects

The dominant feature of the bare patches is thus the absence of living higher plants and the sandy texture. Both characteristics substantially influence the hydrology of the bare patch, which is studied in the next chapter.

Several authors tested the effect of the soil from different fairy circle elements on plant germination and plant growth. Moll (1994) found no difference in the germination of alfalfa (*Medicago sativa*) and *Stipagrostis* grass seeds in the bare patch and matrix. Albrecht (2001) tested the effect of soil from the bare patch centre, bare patch half radius, perennial belt and matrix from Namibrand on the germination of *Cynodon dactylon*. Only plants grown in soil from the perennial belt or matrix survived several cycles of dehydration and rehydration, while plants in the bare patch soil collapsed. Van Rooyen et al. (2004) used *Lolium multiflorum* and tested soils from various localities in Kaokoveld. They found an inhibition of root growth in the bare patch but a stimulation in the perennial belt soil. We did not repeat such experiments due to the lack of a suitable lab. From our own reported field observations (see Chapter 5) we conclude that plant germination in the bare patch is not prohibited by physical, chemical or microbiological processes in general.

7.5 Soil moisture and hydrology of fairy circles

Alexander Gröngröft & Norbert Jürgens

The evolutionary development of fairy circle's bare patches is discussed in this section with respect to the improvement of the survival of soil-dwelling termites in sandy arid landscapes in southern Africa. In these landscapes with approximately 100 mm mean annual precipitation (MAP) and with potential evapotranspiration of > 2000 mm per year, the termites keep patches of the land surface bare and seem to use the within-patch subsoil as a water reservoir for periods without rainfall. Thus the termites are able to continue with their activities during these dry periods. In contrast to the vegetation-covered part of the landscape (the matrix), the soil water storage (SWS) within the area of the bare patch is substantially extended but also restricted. In this chapter, we introduce the involved hydrological processes, report basic observations and try to address some of the hydrological questions of the fairy circles.

Based on a) data from a monitoring programme of soil water contents within the bare patch and the matrix at several sites and b) soil texture data (Chapter 7.4), including theoretical approaches underlined by modelling results, the following hypotheses will be analysed within the this chapter:

(1) The infiltration of rainwater does not differ between the bare patches of fairy circles and the surrounding matrix. There is also no difference in the rainfall-induced vertical percolation of water in deeper soil horizons.

(2) During the vegetation period, the reduction in soil water storage within the matrix is substantially faster due to root extraction.

(3) These differences are especially relevant for the subsoil, as the water loss of the topsoil is not only a matter of root water extraction but also of evaporation.

(4) The topsoils of the bare patches and the matrix are characterised by regular drought during the dry season.

(5) During the dry season, the horizontal water losses from the moister bare patch to the drier matrix are low due to the hydrological properties of the sand.

(6) As a result of the processes highlighted above, in most years, a reservoir of soil water can be found in the subsoil of the centre of the bare patch.

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Water flows and storage in fairy circles—an introduction

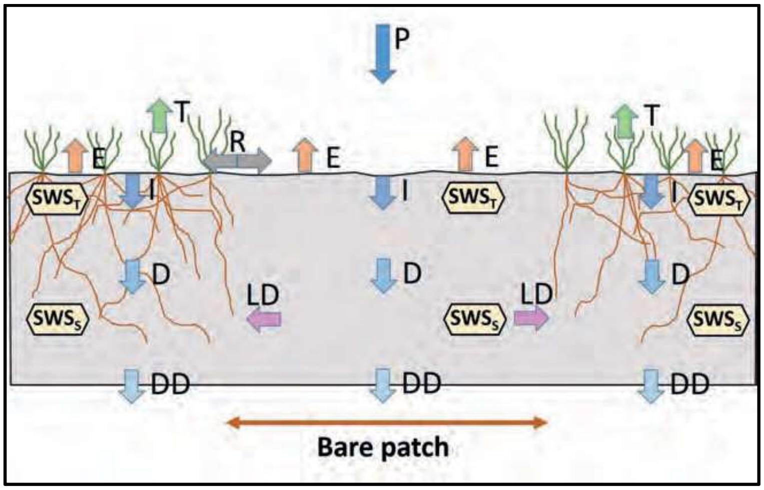


Figure 7.5.1:
Schematic cross-section of a fairy circle with water flows and soil water storage.
P = precipitation;
I = infiltration;
R = run-on and run-off;
D = drainage;
DD = deep drainage;
LD = lateral drainage;
E = evaporation;
T = transpiration;
SWST = soil water storage in topsoil;
SWSS = soil water storage in subsoil.
Graphic: Alexander Gröngröft.

To understand the hydrology of a fairy circle, Figure 7.5.1 shows the relevant water flows of soil water storage schematically.

Precipitation (P) is the only relevant source of water. As shown in Chapter 7.3, the amount of precipitation is restricted to approximately 100 mm per year, but with a high interannual variability.

Infiltration (I) is the amount of water per timestep, which enters the topsoil matrix through the air–soil interface. This results from precipitation (P), which may be modified by interception (N) from the surface of the vegetation and run-off and run-on (R), as in the following equation: I = P (–N) ± R.

Evaporation (E) is the amount of water per timestep that is transferred to the atmosphere directly from the bare soil surface as vapour. If the topsoil is moist, vaporisation takes place directly at the soil surface. With ongoing desiccation, the zone of vaporisation moves into the topsoil, and before entering the atmosphere, the vapour has to diffuse through the soil pores along a concentration gradient.

Transpiration (T) is the amount of water per timestep, which plant roots have taken up and transported within the plant to the above ground tissues and which is transferred to the atmosphere through the leaves as vapour.

Run-off and run-on (R): This process takes place if the rainfall intensity is larger than the infiltration capacity of the topsoil. Under these conditions, water flow at the soil surface follows gravitational forces and collects in small depressions or flows into the next river.

Percolation, drainage (D): Within the soil, water percolates in deeper layers. This process is driven by gravitational and capillary forces and controlled by the hydraulic conductivity of the soil, which depends on the amount of stored water.

Deep percolation or *drainage* (DD) is the amount of water that flows out of the soil compartment below the lower boundary by gravitational forces.

Lateral drainage (LD) is the amount of water that flows out of the moist soil of the bare patch into the surrounding matrix soils following capillary forces.

The a*mount of water stored* (soil water storage) within the soil is indicated as SWS. Here, the topsoil receives water directly by infiltration, whereas in the subsoil, percolation needs to take place to increase the amount of stored water.

$$\Delta SWS_T + \Delta SWS_S = P\ (-R) - E\ - LD - DD$$

For the bare patch soil, a soil water balance equation is given as follows:

$$\Delta SWS_T + \Delta SWS_S = P\ (-R) - E\ - T\ (+LD) - DD$$

In contrast, for the matrix soil, the role of vegetation must be included:

The above given scheme excludes processes which have been found in arid environments and for which the ecological meaning under varying conditions is not fully understood. These non-rainfall inputs of moisture include adsorption, dew condensation and fog combing (Matimati et al. 2013). The condensation of water following temperature gradients is, for instance, possible if, in the morning hours, the topsoil is still colder than the dew point of the ambient air. By high resolution lysimetry, in a Spanish coastal dryland, the amount of this process has been quantified as 0.3–0.4 mm d^{-1} (Kohfahl et al. 2019), and, within the South African Succulent Karoo, Matimati et al. (2013) even reported a total of 59.4 mm in eight months that was adsorbed or condensed from the bare soil. As condensation takes place in the topsoil, which is exposed to solar radiation during the day, the condensed water evaporates back to the atmosphere.

Another possible process within these systems is the fog combing of all biotic and abiotic materials that protrude from the soil surface into the atmosphere. Here, even small elevations are known to be able to collect additional water. However, the fairy circles discussed here are located east of the classical fog zone of Namib, and thus, even the vegetation of the matrix is unlikely to receive additional water by fog combing.

Basic observations on the role of water storage in the soil beneath fairy circles

On the assured basis of years of automated measurements of the soil moisture of fairy circles, we may safely assume that, through the formation of a small initial bare patch (see Chapter 5.1), the most important manipulation of the environment—crucial to the existence of the fairy circles—has already been made. That is, on these few square meters, during the next rainfall event, rainwater will infiltrate into the sandy soil and percolate to deeper layers without being absorbed by the roots of plants and transpired through their leaves to be returned to the atmosphere subsequently, as happens outside the fairy circle.

On the one hand, in a humid climate the difference in moisture triggered by a bare patch of grassland only a few square meters in size would be of little consequence because there is sufficient moisture everywhere in the soil, where it slowly seeps downwards following gravity and is ultimately transferred partly to the groundwater.

On the other hand, the desert has almost permanently dry soil, with mostly dry conditions also in the subsoil. The average annual precipitation provides so little water that only the upper soil layers are supplied with moisture for a limited number of weeks or months, after which the water is transported back up into the atmosphere by evaporation and transpiration. A deep percolating contribution to groundwater recharge is achieved only in exceptional years. Following these conditions, it makes a considerable difference whether a thundershower of 20 mm (i.e., 20 litres of water per square metre) is still available as soil moisture under the bare patch of the fairy circle after ten months or whether the water-consuming vegetation of the grassland outside the bare patch has completely used up these 20 mm after a few weeks and all life processes have come to a standstill again.

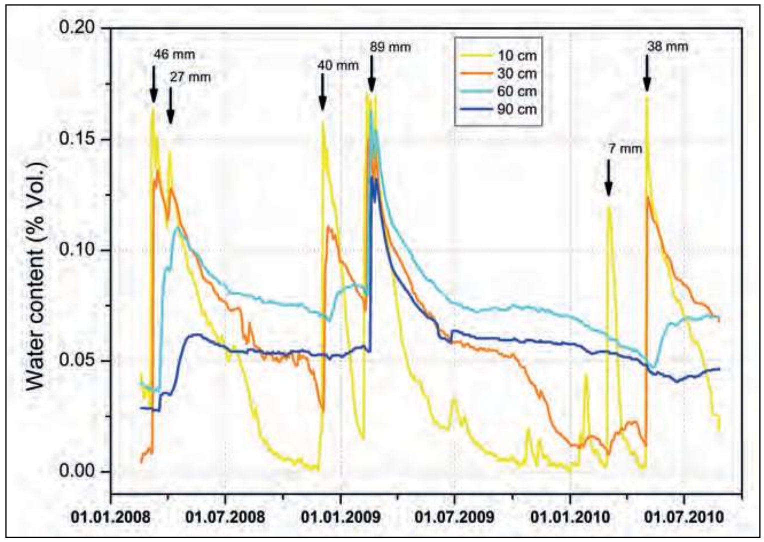
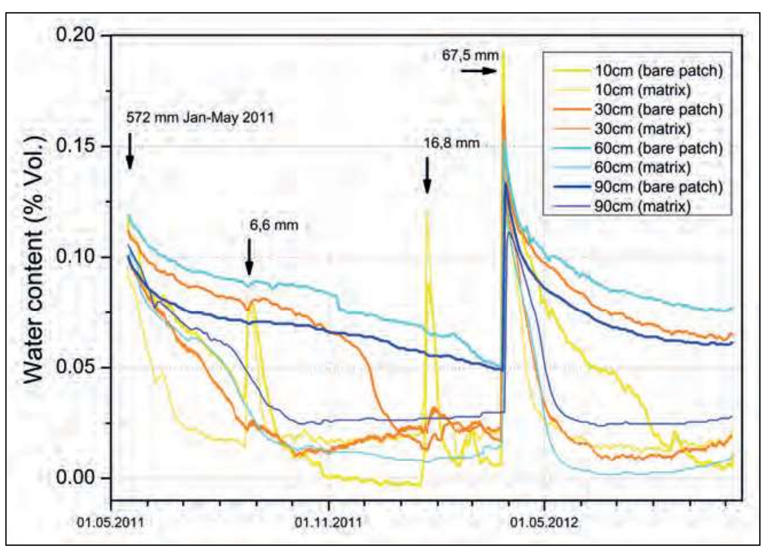


Figure 7.5.2: Water content of the soil beneath the bare patch of the Fairy Circle F15 in Dieprivier in four depths. Rainfall event (black arrows) and amounts (numbers in mm) (Figure from Jürgens 2013).

Since 2008, soil moisture has been measured in bare patches and in the adjacent matrix at many fairy circle landscapes in Angola, Namibia and South Africa. This involved measuring and storing data of a vertical profile of the upper metre with four to five depth layers every hour. The curves in Figure 7.5.2, for example, clearly show how rapidly the water percolates into the coarse-pored sandy soil, reaching a depth of 90 cm after slightly more than a month. At this depth, the rainwater is well protected from evaporation into the dry atmosphere. As a consequence, the amount of water below 60 cm hardly falls below 5 percent by volume during the measurement period. This humidity is likely sufficient to allow the permanent life of the sand termites. Further information on the biology and ecology of sand termites is given in Chapter 4 and 5.

Figure 7.5.3: Water content in the soil of the Fairy Circle F15 in Dieprivier beneath the bare patch (bold lines) and under the matrix in 2 m distance to the perennial belt (thin lines) (Figure from Jürgens 2013).



October 2006, 8 months after rainfall

Depth [cm]	Matrix	Per. Belt	Half radius	Centre	Half radius	Per. Belt	Matrix
10 cm	2.4	2.3	2.7	3.1			
20 cm	2.5	2.6	4.0	4.5			
30 cm	3.0	3.2	4.8	6.0			
40 cm	3.2	4.3	6.0	6.0			
50 cm	3.9	4.6	6.0	6.0			
60 cm	4.4	6.0	6.0	6.5			
70 cm	4.7	6.5	6.5	6.5			
80 cm	5.2	6.5	6.5	6.5			
90 cm	6.0	6.5	6.5	7.0			
100 cm	6.0	6.5	7.0	7.0			
∑H_2O [mm] in 0–100 cm:	**39.1**	**46.6**	**53.3**	**56.4**			

January 2007, 11 months after rainfall

Depth[cm]\Position	Matrix	Per. Belt	Half radius	Centre	Half radius	Per. Belt	Matrix
10 cm	4.6	1.7	3.7	4.6			
20 cm	3.9	2.7	4.7	5			
30 cm	3.6	3.4	6.2	6.7			
40 cm	5.4	4.3	5.9	6.4			
50 cm	4.3	3.9	6.4	6.2			
60 cm	3.7	3	6.8	7.6			
70 cm	5.1	3.6	5.6	9.1			
80 cm	3.8	4.7	6.7	6.7			
90 cm	4.9	5	5	7.0			
100 cm	4.7	5.2	5.9	6.8			
∑H_2O [mm] in 0–100 cm:	**44.0**	**37.8**	**55.8**	**65.0**			

March 2007, after 28 mm rainfall in total from January to March 2007

Depth[cm]\Position	Matrix	Per. Belt	Half radius	Centre	Half radius	Per. Belt	Matrix
10 cm	4.9	4.6	5.3	4.4			
20 cm	5.9	5.4	7.2	8.9			
30 cm	6.0	5.6	9.3	9.1			
40 cm	5.3	5.5	8.6	9			
50 cm	5.2	5.6	8.2	9.2			
60 cm	4.1	5.5	8.5	8.8			
70 cm	5.2	5.4	9.1	9.4			
80 cm	4.9	5.2	9	9.5			
90 cm	4.9	5.4	9.2	10.1			
100 cm	4.6	5.3	8.2	9.9			
∑H_2O [mm] in 0–100 cm:	**51.2**	**53.2**	**81.2**	**85.6**			

10 February 2008, 5 days after approximately 25 mm rainfall

Depth[cm]\Position	Matrix	Per. Belt	Half radius	Centre	Half radius	Per. Belt	Matrix
10 cm	8.9	8.5	5.2	7.7			
20 cm	5.2	5.9	5.9	6.2			
30 cm	3.4	4.9	5.5	6.8			
40 cm	3.4	3.6	5.3	5.1			
50 cm	4	4	5	6.8			
60 cm	4.2	4.3	6.3	7.3			
70 cm	4	4.1	6.2	7.6			
80 cm	4.1	3.9	7.0	6.5			
90 cm	4.5	4.3	7.1	7.4			
100 cm	4.5	4.3	7.1	7.4			
∑H_2O [mm] in 0–100 cm:	**48.4**	**49.9**	**59.7**	**69.0**			

December 2007, 8 months after rainfall

Depth[cm]\Position	Matrix	Per. Belt	Half radius	Centre	Half radius	Per. Belt	Matrix
10 cm		2.7		3.2			
20 cm		3.4		4.9			
30 cm		2		3.9			
40 cm		3.9		5			
50 cm		4.5		5.9			
60 cm		3.6		6.4			
70 cm		4.2		6.1			
80 cm		4.2		6.4			
90 cm		4.2		6.4			
100 cm		5.1		6.4			
∑H_2O [mm] in 0–100 cm:		**36.6**		**53.0**			

Table 7.5.1: Soil moisture storage (the darker the blue, the wetter the level) at different dates. The three middle columns (half radius, centre, half radius) mark the bare area of the fairy circle (Figure from Jürgens 2013)

The significance of the bare ground becomes even clearer when contemporaneous measurements are taken under the fairy circle and under the grass-covered matrix 2 m outside the perennial belt and plotted on a graph (Fig. 7.5.3). Compared to the soil under the fairy circle bare ground, water entering the soil from rain events in the MT is rapidly consumed by the grass cover that germinates after rain, grows and transpires water in the process.

These data demonstrate that under each fairy circle, even during prolonged periods of drought, there is a water reservoir that may be interpreted as an underground oasis in the desert. As the series of measurements in Figure 7.5.2 and Figure 7.5.3 show, the amount of water stored depends on the history of previous precipitation. To record the spatial distribution of moisture, several fairy circles were excavated to a depth of 1 m and the water content measured in steps of 10 cm depth (Tab. 7.5.1). Here, the data show that the rainwater after precipitation under the bare patch quickly sinks to this depth, while the grass of the MA and the perennial belt consumes most of the water like a filter. Figure 7.5.6 shows the typical trench used in the measurements for the moisture contents.

Equally predictable is that some of the water stored in the soil escapes to the atmosphere by evaporation. A side effect of this evaporation is a cooling of the soil of the bare patch, as demonstrated by Vlieghe (2019), often measured in soil profiles and shown in the snapshot thermal image in Figure 7.5.4.

Table 7.5.1 also shows that in the January 2007 soil moisture distribution, the soil under the perennial belt had the driest values. The series of measurements from Angola in Figure 7.5.5 also recorded a temporal phase during which the lushly developed perennial belt, with its large grass horsts of *Stipagrostis giessii*, had the greatest water consumption and, accordingly, the driest soil values. Thus, there are periods when the soil beneath the perennial belt is the deepest sink for water.

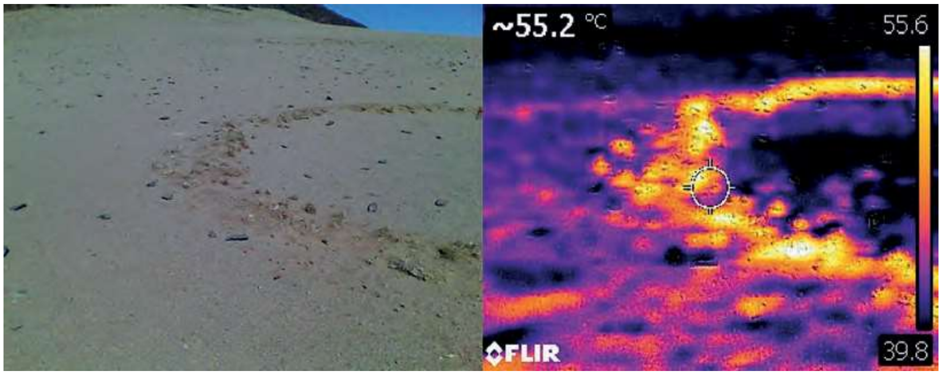


Figure 7.5.4:
Fairy Circle 32515 at C27 south of Sesriem is shown in visible wavelengths on the left and as a thermal image on the right. The soil surface of the bare patch with only approximately 40°C (black) is much cooler than the soil surface of the MA, at approximately 45 to 47°C (purple to orange).

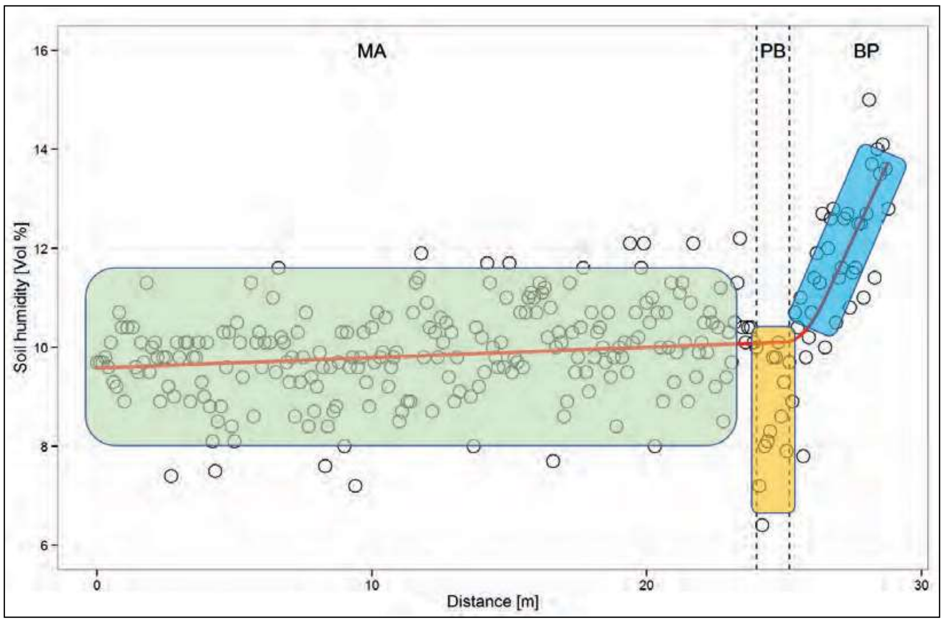


Figure 7.5.5:
Water content of the topsoil in the matrix (MA, green), perennial belt (PB, yellow) and bare patch (BP, blue). The long-lived grass plants of the PB exploit the water in the soil more than the short-lived grasses in the MA. In the transition to BP, the soil water content increases steeply.

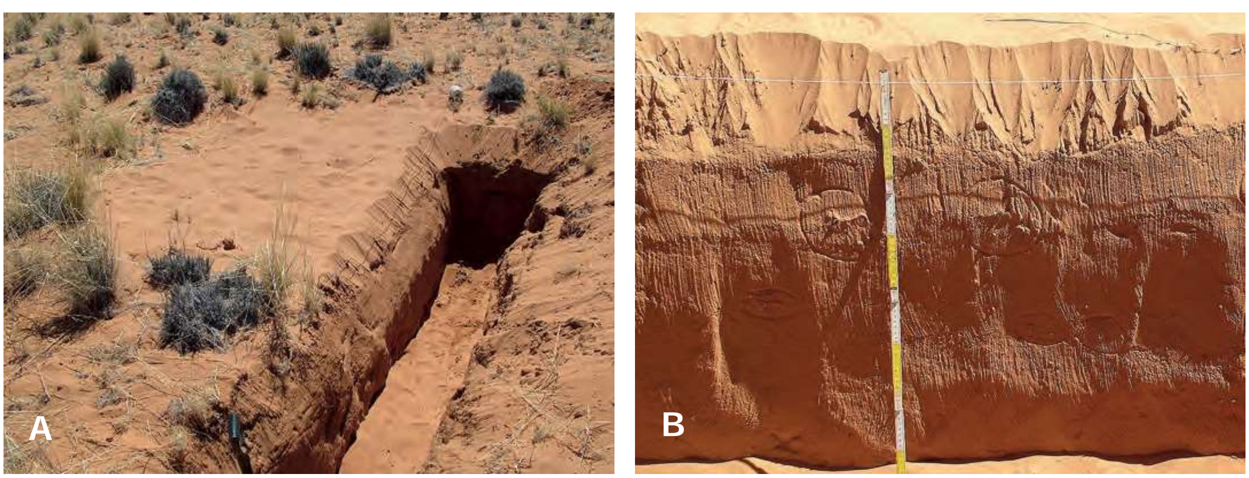


Figure 7.5.6 A and B:
To collect the measurements for Table 7.5.1, at many localities a 1 m deep trench was excavated as a tangent slightly outside the centre of a fairy circle. Samples were then taken from a freshly trenched profile wall, and measurements of temperature and water content (TDR moisture probes) were made by pressing the sensors laterally into the soil profile at 10 cm intervals. Note the tunnels of *Psammotermes* beneath the bare patch (Rostock, 04.10.2006).

Infiltration of rainwater

The infiltration of rainwater into the soil is the first process among the different soil water fluxes (Fig. 7.5.1). The amount of infiltrating water depends on rainfall intensity, rain-catching plants and other material above the soil surface and on the capacity of the soil to let the raindrops infiltrate into the soil pores. If the rainfall exceeds the soil infiltration capacity, water accumulates on the soil surface and, depending on the topography, tends to flow in deeper positions. If this run-off occurs, the amount of infiltrated water may be less than the amount of rainfall. Moreover, if positions in depressions are considered, the amount of water entering the soil may be much larger than the amount of rain due to run-on.

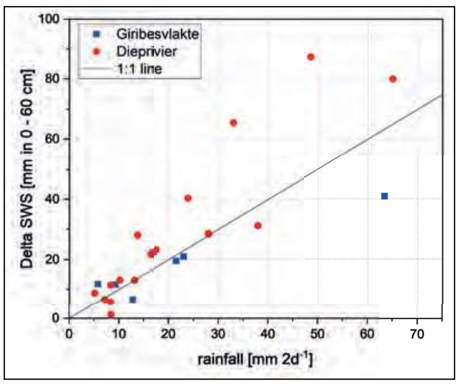


Figure 7.5.7: Increase in SWS under the bare patch in relation to the amount of rainfall for the study sites Dieprivier und Giribesvlakte: .

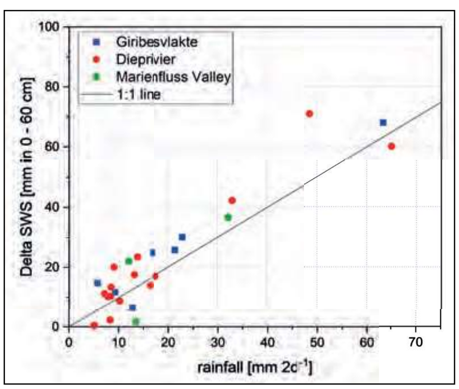


Figure 7.5.8: Increase in SWS under the matrix in relation to the amount of rainfall for the study sites Dieprivier, Giribesvlakte and Marienfluss Valley.

As shown in Chapter 7.4, the topsoil texture in the landscapes with bare patches is sandy. The infiltration capacity of sands is generally high, and only strong topsoil compaction, the development of surface crusts or the occurrence of water repellency could be reasons for a reduced infiltration capacity. The data on the soil water monitoring of bare patches and the surrounding matrix were thus analysed regarding the questions of whether run-off events are occurring and whether the amount of infiltration differs between bare patch soils and matrix soils.

To investigate the water balance of fairy circles, we established at ten sites in Angola, Namibia and South Africa a soil water monitoring experiment with soil moisture sensors at three to five depths in the bare patch, the perennial belt and the matrix. Based on the data of three soil water content sensors at each position (at depths of 10, 30 and 50 cm), the mean amount of SWS was calculated and averaged per day. The daily means of SWS clearly indicate the effect of infiltrating rainwater. Figure 7.5.7 shows the increase in SWS within the upper 60 cm of the bare soil patch following a rain event for two study sites (Giribesvlakte and Dieprivier). The general trend is clearly visible: the more rain there is, the greater the increase in soil moisture. For the Dieprivier site, a tendency for a slightly higher increase in soil moisture compared to the rain amount is visible, but not for the Giribesvlakte site. The amount of rainfall in the analysed events reaches more than 60 mm, which includes very strong rain events.

Figure 7.5.8 shows the same relation for the respective matrix soils. In this case, some data from the monitoring site Marienfluss Valley also exist. Additionally, for the matrix soils, the increase in SWS follows the amount of rain. In the case of lower rain amounts (< 15 mm per event), there is some scatter in the data; however, at stronger rain amounts, the relation is rather strong. This includes one rain event at each site (Giribesvlakte and Dieprivier) with > 60 mm rain.

To compare the infiltration rates between the bare patches, the perennial belt (only Giribesvlakte) and the matrix, for all events with substantial infiltration rates (> 10 mm), quotients between the rates were calculated. This resulted in the following:

- mean relation between ΔSWS of bare patches and ΔSWS of matrix – Giribesvlakte: 0.84 (n = 9)
- mean relation between ΔSWS of bare patches and ΔSWS of matrix – Dieprivier: 1.34 (n = 10)
- mean relation between ΔSWS of bare patch to ΔSWS of matrix – Marienfluss Valley: 0.72 (n = 3)
- mean relation between ΔSWS of perennial belt to ΔSWS of matrix – Giribesvlakte: 0.76 (n = 9)

This comparison demonstrates that the relation is site specific and not generally similar for all analysed fairy circles. The difference between the increases in SWS is likely due to slight differences in soil properties around the sensors. If around one sensor the soil is slightly more compacted, the logged volumetric water content (VWC) is slightly larger than the actual surrounding VWC. However, within the calculation of the SWS, we assume that the soil within a depth interval of 20 cm (e.g., for the sensor at 30 cm depth from 20 to 40 cm) has equal moisture.

Based on the soil water monitoring data, we can conclude the following:

- For up to 60 mm of rain per event, the bare patch and the matrix soils are able to infiltrate the rainwater without run-off.
- The amount of infiltrated water does not generally differ between the bare patch and the matrix.

Percolation into the subsoil

Once infiltrated, the soil water is bound by capillary forces, and water flow to deeper layers is controlled by the unsaturated hydraulic conductivity of the soil. As an example, Figure 7.5.9 (right) shows the results of the hydraulic conductivity function of four samples from the Dieprivier site. The samples were prepared in the laboratory, the hydrological soil properties measured with the HYPROP procedure and the resulting values fitted with the original Mualem–van Genuchten equations.

The four samples did not show any significant difference in hydraulic behaviour. As typical for sandy material, the hydraulic conductivity, which is large near saturation (low suction pressure, high water content), reduces strongly with increasing suction or reducing water content (see logarithmic conductivity scale). The strong reduction in conductivity starts at approximately 6–8 vol% of the VWC. This means that the topsoil layer needs to be wetted by rainfall to more than approximately 8 vol% before a capillary flow in deeper horizons is possible.

As a result of 11 years of soil water monitoring at the Dieprivier site, the following graphs (Figures 7.5.10–7.5.13) show the course of soil moisture (measured as volumetric water content VWC) at four depths by comparing the moisture in the bare patch with the respective values of the surrounding matrix. The data are influenced by some gaps and slightly varying offsets, as the applied sensors have the problem of quantifying miniscule amounts of water in the surrounding soil in the case of desiccation. However, the data allow us to demonstrate the soil water relations nicely as follows:

- At the 10 cm soil depth (Fig. 7.5.10), the soil water content is characterised by numerous peaks and subsequent drying of the soil. As expected, the peaks in the bare patch occur at the same moment as the nearby matrix position. The peaks are directly related to rainfall and vary with regard to the VWC between approximately 5 and 19 vol%. For the bare patch soil, the sensors indicated a minimum VWC

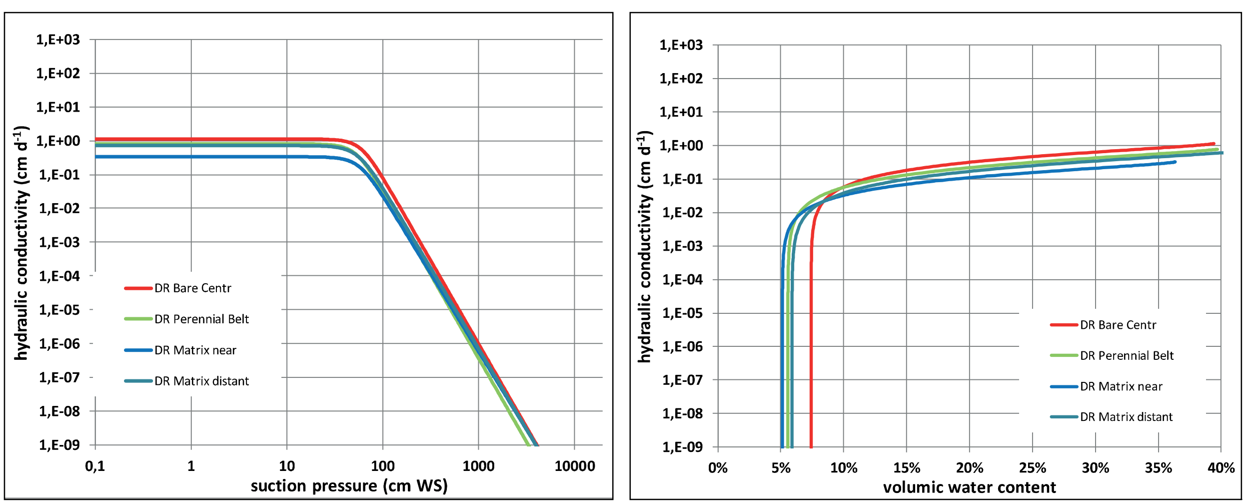


Figure 7.5.9: Unsaturated hydraulic conductivity of soil samples from Dieprivier in relation to suction pressure (left) and volumetric soil water content (right).

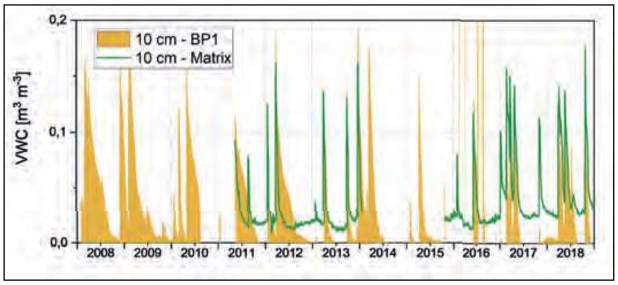


Figure 7.5.10: Eleven-year fluctuations of volumetric water contents at the Dieprivier site—comparison between the bare patch and matrix at the 10 cm soil depth.

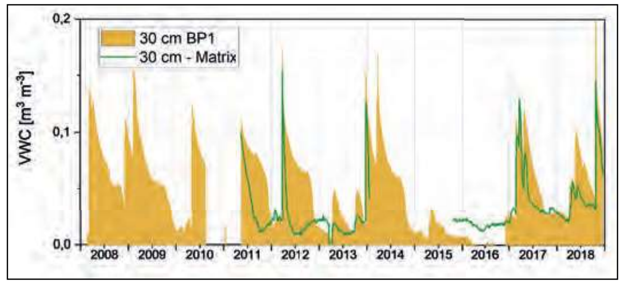


Figure 7.5.11: Eleven-year fluctuations of volumetric water contents at the Dieprivier site—comparison between the bare patch and matrix at the 30 cm soil depth.

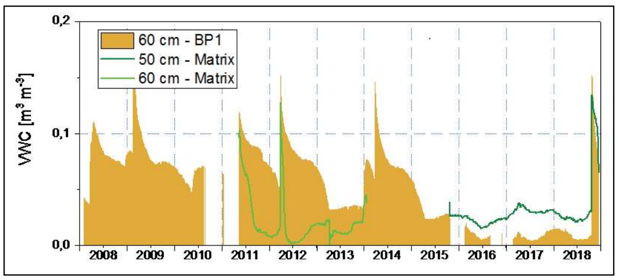


Figure 7.5.12: Eleven-year fluctuations of volumetric water contents at the Dieprivier site—comparison between bare patch and matrix at the 50 or 60 cm soil depth.

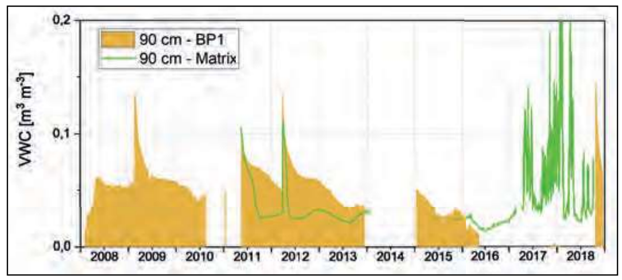


Figure 7.5.13: Eleven-year fluctuations of volumetric water contents at the Dieprivier site—comparison between the bare patch and matrix at the 90 cm soil depth.

after desiccation of approximately 0 vol% and at the matrix soil at approximately 2 vol%. This difference is interpreted as an artefact of the sensor definition..

- At the 10 cm soil depth (Fig. 7.5.10), the soil water content is characterised by numerous peaks and subsequent drying of the soil. As expected, the peaks in the bare patch occur at the same moment as the nearby matrix position. The peaks are directly related to rainfall and vary with regard to the VWC between approximately 5 and 19 vol%. For the bare patch soil, the sensors indicated a minimum VWC after desiccation of approximately 0 vol% and at the matrix soil at approximately 2 vol%. This difference seems to be artificial.

- At the 30 cm depth (Fig. 7.5.11), the number of peaks decreased, and, especially at the bare patch position, the change in soil moisture was much slower. The height of the peaks varies between 3 and 17 vol%, with the exception (in October 2018) being 21 vol%. As far back as the data exist, the peak position and height are almost the same at the bare patch position and the matrix position. However, both positions differ extremely in the changes of soil water content after the peaks. For the bare patch position, the reduction in soil moisture shows a significant shoulder at approximately 5 to 7 vol%, which equals the above given water content at which the hydraulic conductivity strongly reduces. In contrast, in the matrix position the reduction of soil moisture after the peaks reduces very fast to almost constant values.

- At the 50 to 60 cm depth (Fig. 7.5.12), the peak height is approximately 15 to 16 vol% at the bare patch and approximately 13 vol% at the matrix position. The number of peaks is reduced further; however, as long as data exist at both positions, the peaks occur simultaneously.

- In the deepest soil layer (90 cm; Fig. 7.5.13), there are only a few peaks of water contents visible. The peak height is approximately 13 vol% in the bare patch and approximately 11 vol% in the matrix.

In Table 7.5.2 all peaks are listed, for which robust data on rain amounts from the nearby SASSCAL

Table 7.5.2: Rain events and soil moisture peaks at the Dieprivier site (delay = number of days between rainfall and peak; PH = peak height, NP = no peak; MV = missing value; ?? = values varying)

Date of rain	Rain	Bare patch						Matrix					
		30 cm		60 cm		90 cm		30 cm		50–60 cm		90 cm	
		delay	PH	delay	PH	delay	PH	delay	PH	delay	PH	delay	PH
	mm	d	vol%	d	vol%	d	vol%	d	vol%	d	vol%	d	vol%
29.03.2018	13.1	28	5.90	1	1.51	NP		12	3.24	16	2.63	??	
26.09.2013	13.7	23	4.82	NP		NP		23	2.65	24	2.14	NP	
18.05.2018	16.4	11	10.00	NP		NP		21	5.22	NP		NP	
31.03.2013	17.5	29	4.83	NP		NP		MV		NP		NP	
19.04.2017	19.8	5	11.95	NP		NP		15	8.24	NP		??	
16.03.2014	23.9	9	16.96	10	14.64	MV		MV		MV		MV	
10.04.2015	28.0	29	3.14	NP		NP		MV		MV		MV	
21.12.2013	34.7	2	15.18	35	7.69	MV		4	12.63	25	4.54	NP	
22.10.2018	65.0	1	21.02	3	15.24	3	14.56	2	14.52	4	13.39	MV	
26.03.2012	67.5	1	17.40	2	15.24	2	13.42	1	15.49	2	12.75	6	11.13

weather station exist, based on the peaks visible at the 30 cm soil depth. The table is sorted by rainfall intensity and reports peak height (in vol%) and the delay between rainfall and peak occurrence. The data demonstrate the following:

- In the case of strong rain events (60–70 mm rain), the infiltrating water leads to peaks at 30 cm the day after rainfall, at 60 cm 2 to 4 days later and even at 90 cm depth with only a two- to six-day delay. The percolation is thus rapid and increases the soil moisture up to 11% at depth and up to 21 vol% at 30 cm.

- An intermediate rain event of 34.7 mm percolates down to 60 cm in the bare patch and in the matrix; however, the increase in subsoil moisture needed 25 to 35 days before the peak was observed. As far back as data are available, no percolation to 90 cm could be detected.

- Lower rain amounts (13–28 mm) need more time to moisten even the 30 cm depth (5–29 days' delay), and only as an exception do they result in small moisture peaks at 60 cm depth, but never at 90 cm depth.

The comparison between the bare patch and the matrix with regard to water percolation does not result in substantial differences. However, in the matrix position, the height of rainfall-induced moisture peaks is always smaller.

Estimation of lateral water drainage

Regarding the higher contents of soil moisture within the bare patch area compared to the adjacent matrix, soil capillary forces are able to result in horizontal water fluxes from the moist bare patch into the matrix (Fig. 7.5.1). These fluxes reduce the water storage in the bare patch. To demonstrate the dominant controlling factors, we present the results of a rough estimate of horizontal water fluxes based on the classical soil water flow concept. For this estimate, we defined a moist soil circle (BP) of varying radius R and a thickness of 0.1 m. We set the initial soil water tension of the bare patch (ψ_i) with 60 cm WC

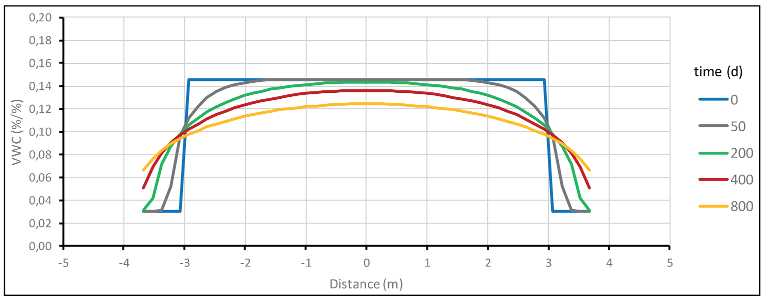


Figure 7.5.14: Change in volumetric water content (VWC) of a medium sand due to lateral drainage.

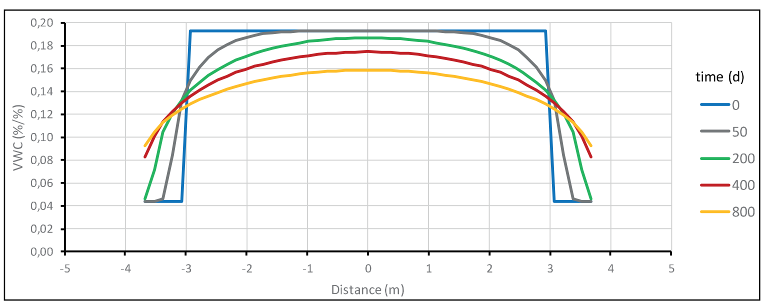


Figure 7.5.15: Change in volumetric water content (VWC) of fine sand due to lateral drainage.

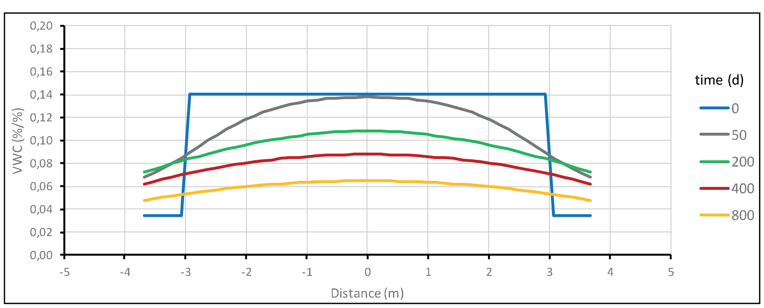


Figure 7.5.16: Change in volumetric water content (VWC) of a Kalahari dune sand (medium sand with slight clay and silt proportions) due to lateral drainage.

(field capacity), the initial soil water tension of the matrix (ψ_o) with 5,000 cm WC (near-permanent wilting point) and the time step (t) with 720 min. Based on these definitions, the change in soil moisture along the transition through the bare patch and the matrix was calculated.

a) Influence of soil texture

Keeping the radius of the bare patch constant (R = 3 m), Figures 7.5.14–7.5.16 demonstrate the role of the texture of the sand on the horizontal water losses. Using the reported hydrological parameters for medium sands (from Renger et al. 2009), the VWC of the bare patch is strongly protected against horizontal water losses due to very low hydraulic conductivities under dry conditions. Even after approximately two years (800 d), approximately 12 vol% of water is still stored in the centre of the bare patch. With a soil moisture tension of approximately 95 cm WC, this sand is still moist.

A shift to fine sands (VGP from Renger et al. 2009; Fig. 7.5.15) leads to an enlarged water storage within the bare patch under moist conditions but also to a more prominent horizontal water loss with time. Under these conditions, after approximately two years, in the centre of the bare patch, the soil moisture tension reached 110 cm WC.

The third example (VGP measurements; Fig. 7.5.16) shows the estimated horizontal water losses of a sand sampled in the subsoil of a profile in northern Namibia. This sand has equal shares of fine and medium sand, approximately 5.3% clay and 4.3% silt. The larger proportion of fine-grained particles enlarges the unsaturated hydraulic conductivity, and thus, the horizontal loss in soil water is faster. Even after 200 days, the water loss in the centre of the bare patch is clearly visible.

b) Influence of bare patch diameter

The diameter of the bare patch is of significant importance for the temporal storage of water within the bare patch. For the example of fine sand (as in Figure 7.5.15), the next five graphs show the change in VWC within a bare patch of increasing diameter (3 m to 7 m). For the smallest bare patch, the loss in VWC is significant even after 200 days. With increasing diameter, the water within the bare patch centre is increasingly better protected against horizontal capillary water losses.

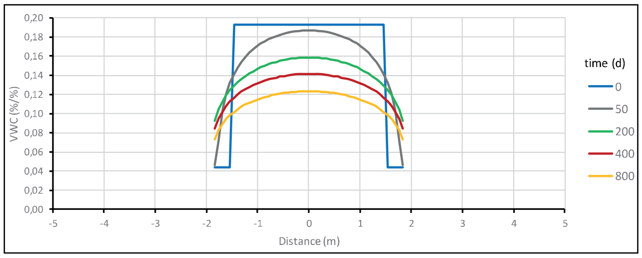


Figure 7.5.17: Change in volumetric water content (VWC) of a fine sand due to lateral drainage: bare patch radius 1.5 m.

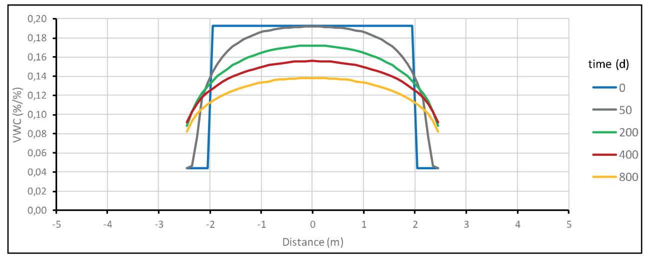


Figure 7.5.18: Change in volumetric water content (VWC) of a fine sand due to lateral drainage: bare patch radius 2 m.

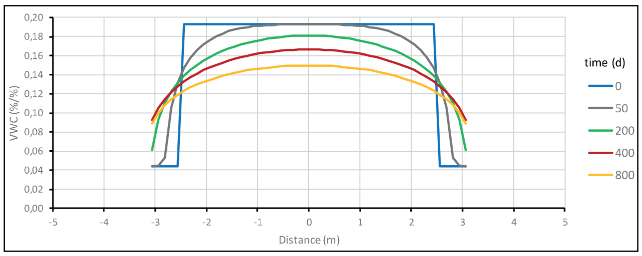


Figure 7.5.19: Change in volumetric water content (VWC) of a fine sand due to lateral drainage: bare patch radius 2.5 m.

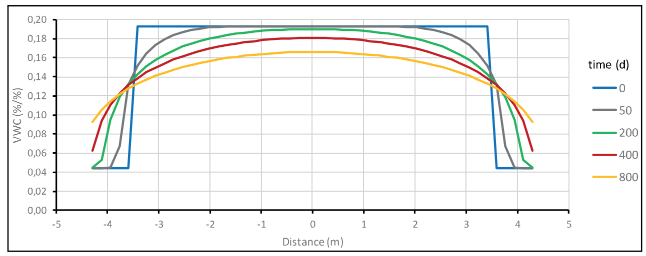


Figure 7.5.20: Change in volumetric water content (VWC) of a fine sand due to lateral drainage: bare patch radius 3 m.

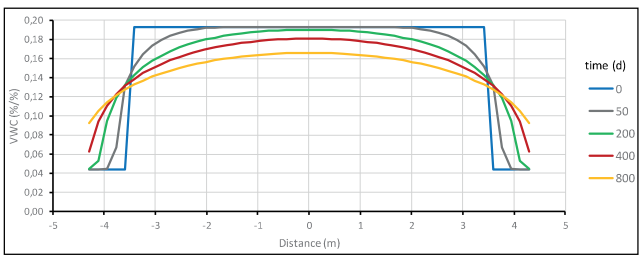


Figure 7.5.21: Change in volumetric water content (VWC) of a fine sand due to lateral drainage: bare patch radius 3.5 m.

To summarize, the horizontal water loss of a moist bare patch in a dry matrix due to capillary water movement is controlled by the hydrological properties of the soil material and the diameter of the bare patch. Pure sands are characterised by exceptionally low unsaturated hydraulic conductivities in the below field capacity moisture range. As a result, in these substrates, the within-patch moisture is well protected against lateral drainage. Increasing amounts of fine particles (clay and silt and most likely also humus) even in the soil texture class "sand" lead to enlarged hydraulic conductivities and thus to faster water loss through horizontal capillary waterflows.

With increasing diameter of the bare patch, the within-patch water storage improves. Small bare patches are thus the first ones which lose their water through capillary forces. However, in pure sands, even in a bare patch of only 3 m in diameter, the moisture may be stored for one dry season.

Irrespective of the lateral drainage analysed here due to capillary water movement, under in situ conditions, there are additional processes leading to water losses. This may be due to the vertical flows to the deeper underground in the case of lower soil moisture tension, the uptake of water by roots in the outer part of the bare patch and, especially, the loss of water to the atmosphere due to the diffusion of vapour through the coarse and almost dry topsoil. Additionally, the transport of moist soil particles to the soil surface by termites may increase evaporative water losses from the bare patch; however, the analysed systems are not driven by mount-building termites and the transport of wet material may play only a minor role. Thus, the above analyses on lateral drainage are thought to underline the fact that the potential benefit of bare patches in sandy substrates for desiccation sensitive sand termites has a clear physical background.

Water losses through evaporation and transpiration

In drylands, the absolutely dominating waterflow from the soil is driven by the atmosphere, either by direct vaporisation from the soil surface (= evaporation) or by root water uptake, liquid flow within the plant tissues and final transfer at the plant surfaces to the ambient air (= transpiration; see Figure 7.5.1). By theory, ongoing evaporation of a moist soil follows three phases (Wang 2015). In phase one, as long as the topsoil is moist enough, liquid water flows within the soil capillaries to the soil surface, where vaporisation takes place. The rate of evaporation is controlled by the incoming heat and the air properties (temperature, humidity and velocity) but not by the soil properties. In phase two, the uppermost parts of the soil dry out and vaporisation takes place slightly below the soil surface. Under these conditions, incoming heat and soil properties (porosity) control evaporation, which is lower than in the first phase. In phase three, a dry topsoil layer of 10–20 cm has developed, and the zone of vaporisation has moved down to this depth. Now, the heat flow from the soil to the atmosphere controls evaporation, which is stronger at night than during the daytime. If during this process of desiccation intermediate small rainfall takes place, the phases may overlap. Of course, the three described phases and the relevant depths of this concept are also governed by soil texture and the different abilities of capillary rise and saturated and unsaturated water flow.

Additionally, transpiration is typically modelled in three phases of soil moisture status (Feddes et al. 2001). In phase one, as long as the soil within the rooting zone is moist (field capacity or slightly drier), transpiration is optimal and only controlled by the atmosphere and thus equals the potential transpiration. With ongoing soil water reduction, plants cannot absorb as much water as possible. In phase two, transpiration is governed not only by the atmospheric conditions but also by the soil moisture. In this phase, transpiration is below the optimum level and reduces with ongoing soil desiccation. In phase three, the soil moisture is too low for root water uptake, and thus transpiration stops. The soil moisture status at which this phase starts is named the wilting point.

To demonstrate the difference between the evapotranspiration of the bare patch and the matrix, Figure 7.5.22 shows the course of the amount of water stored in the upper 60 cm of the soil after three distinct rain events at the Dieprivier site. For these events, no further rain was observed. For the first event (May 2011), the weather station was not yet working; thus, the total rainfall amount was unclear. In March 2012, 67.5 mm of rain was registered on two consecutive days, and, in December 2013, 34.8 mm was registered on four days. As no deep drainage was possible at these events, the changes can be viewed as losses of water by evaporation at the bare patch position and evaporation plus transpiration at the matrix position.

This analysis allows us to conclude the following:

Within the first five to seven days after the rain event, the transfer of water back to the atmosphere starts with high values (2.5–4 mm d^{-1}) but

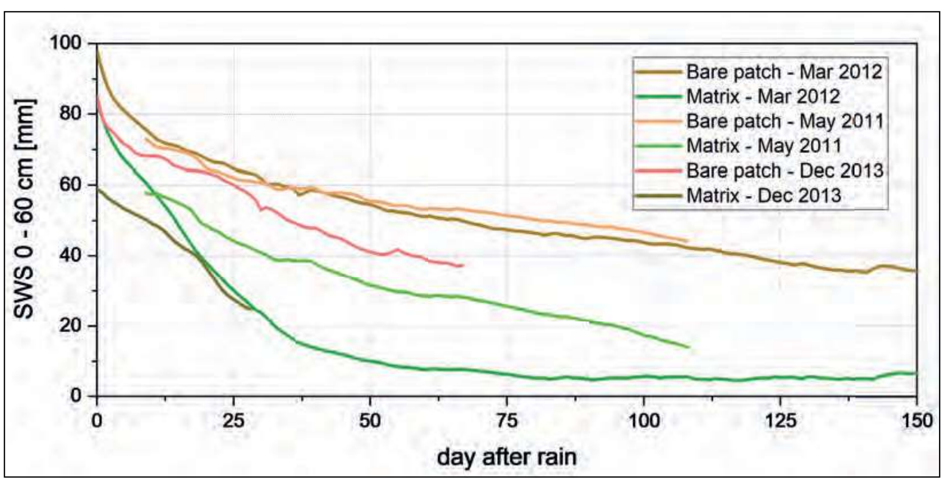


Figure 7.5.22: Changes in soil water storage (SWS) in the upper 60 cm of soil after three distinct rain events at the Dieprivier site—comparison of bare patch and matrix.

reduces to 1.2 mm d^{-1} in the mean at both positions. Thus, in this period, no significant differences are observed.

Whether a difference in the course of evapotranspiration between both positions (bare patch and matrix) occurs depends on the season and, thus, on the development stage of the grasses within the matrix. In May, where the grasses have finished seed production and dried, no further transpiration takes place, and the soil moisture losses between bare patches and the matrix are similar. The early season rain in December 2013 resulted in similar water losses in the first week; however, evapotranspiration increases at the matrix position started approximately ten days after the rain. The fast-developing grasses consumed approximately 26 mm of soil water within the next 18 days, whereas the evaporation at the bare patch was only 11 mm during this period.

The most significant difference between the ET at both positions occurs when the grasses are well developed. This could be observed in March 2012 (Fig. 7.5.23). Within 40 days (i.e., until the beginning of May), the SWS was used up by the grasses almost completely. Here, the mean ET was 1.5 mm d^{-1}, and in total, 55 mm was evaporated and transpired. In the bare patch, the mean evaporation was 0.66 mm d^{-1}, and, 40 days after rain, 30 mm of water was still stored in the upper 60 cm of the soil. In the following two months, the higher water reserves resulted in slightly higher evaporative water losses in the bare patches than in the matrix. The mean evaporation from days 41 to 100 was 0.13 mm d^{-1} in the matrix and 0.25 mm d^{-1} in the bare patch.

Conclusions on the role of the soil properties

Fairy circles occur in plain landscapes on deep sandy soils with characteristic soil water relations. These soil conditions are essential for the survival of the termites. The current knowledge on the role of soil properties can be summarised as follows:

Both parts of the landscape—the bare patch and the surrounding matrix—receive the same amount of water by the infiltration of rainwater. This is promoted by the high infiltration rate of the sandy topsoil and the almost plain areas where fairy circles generally occur. Run-off and run-on effects are not identified in the data; however, extreme thunderstorms may have an effect. Unrestricted rainwater infiltration is also assumed for those fairy circles, where rock or calcrete fragments cover the soil surface. The storage of water in the subsoil depends on the occurrence of rain events, which are sufficient to moisten the topsoil (0–30 cm) to > 6 vol% of soil water. This is the threshold when percolation to deeper horizons becomes substantial. The climatic frame conditions are characterised by low mean annual rainfalls (approx. 100 mm). Reliable rainfall recordings in the respective regions are scarce. In six years of climate observation at the Giribesvlakte station (2015–2021), five events with sufficient rain to drain into the 30 cm soil depth have been registered. These events occurred within the rainy season (early December to mid-April).

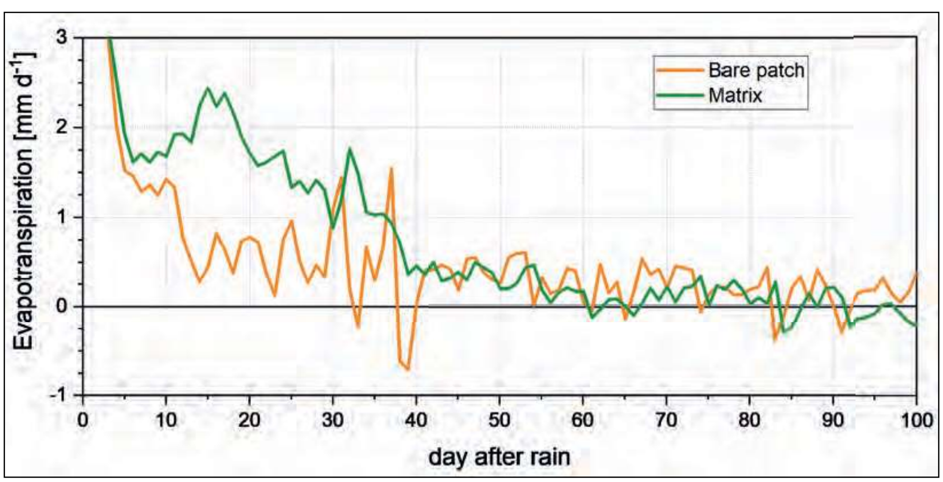


Figure 7.5.23: Calculated daily evapotranspiration after a rain event on 26–27 March 2012 at the Dieprivier site.

Two consecutive seasons without sufficient rainfall to moisten the subsoil took place. Of the five rain events in total, both in April (19.04.2017 and 15.04.2018) were strong enough to moisten the subsoil to more than 50 cm soil depth. In ten seasons of climate observation at the Dieprivier station (2011–2021), in half of the seasons no rain events occurred, which could have moistened the subsoil. For the other five seasons, in total, seven events were observed that were likely to moisten the soil down to 30 cm depth in three cases in three years, even down to 50 cm. Although it is not proven, if all rain events were registered correctly, we can conclude that the preservation of subsoil water within the bare patches is only possible in some seasons and that termites need to be able to survive these years of missing soil water.

The almost complete consumption of soil water through root water uptake and transpiration within a few weeks at the matrix sites could be properly demonstrated with the data. In contrast, on the bare patch, subsoil water is preserved from evaporation. Here, the mean water losses are quantified as approximately 0.25 mm d^{-1}, which means that, in six months, approximately 45 mm of water is lost.

The hydrological properties of the sand are responsible not only for the occurrence of a dry topsoil above a moist subsoil on the bare patch but also for only small amounts of horizontal water losses from the moist bare patch to the dry surrounding matrix.

As a consequence of the above results, the seasonal likelihood of the occurrence of a soil water reservoir below a bare patch cannot be quantified properly. Here, rare thunderstorms with high rainfall amounts play a dominant role. Precipitation events of 89 mm or 67.5 mm, as demonstrated in Figure 7.5.2 and Figure 7.5.3, create a long-lasting reservoir of subsoil moisture within the bare patch but also in the production of high amounts of grassy biomass in the grassy plains. A shift in rainfall patterns as a consequence of climate change might be critical for the survival of fairy circles.

In relation to the amount of water stored within the subsoil of a bare patch, the relative amount of horizontal water losses from the bare patch to the matrix through capillary forces decreases with an increasing diameter of the bare patch. Keeping the rare rainfall events in mind that are able to fill up the subsoil water reservoir, for the termites it is much easier to keep existing bare patches in place than to establish a new bare patch of sufficient diameter within a period of a few weeks, where plants normally transpire almost all water from the subsoil reservoir.

The formation of the perennial belt is an inevitable side effect of the storage of moisture underneath the bare patch. The growth of grass tussocks and their water allocation via roots may cause a minor flow of some nutrients towards the perennial belt. However, this does not result in a longer-term nutrient accumulation, as the position of the perennial belt is dynamically shifting towards the outside or the inside of the fairy circles (compare Chapter 5.3).

7.6 Methane and other gases are released from fairy circle bare patches

Fairy circles are inevitably connected with an output of numerous gases and semivolatile substances, including substances known to come from oil and gas fields. Jankowitz et al. (2008) set up a field experiment in a fairy circle bare patch with grass plants in containers that were either closed or open at the bottom. They found reduced vitality in the containers that were open at the bottom and concluded that semivolatile gas (of unknown compounds) from the fairy circle soil inhibited plant growth. When collecting soil samples for gas chromatography-mass spectrometry (GC–MS) analyses in the course of the study by Stefanie Kaffarnik and Stefan Franke at the Chemical Department of the University of Hamburg in 2008 and 2009, the dimension of such compounds was so large that the authors were asked whether the samples could have been contaminated with diesel. However, a second collecting trip with extremely careful control of the samples brought the same results, which was published in Kaffarnik (2009). Additionally,