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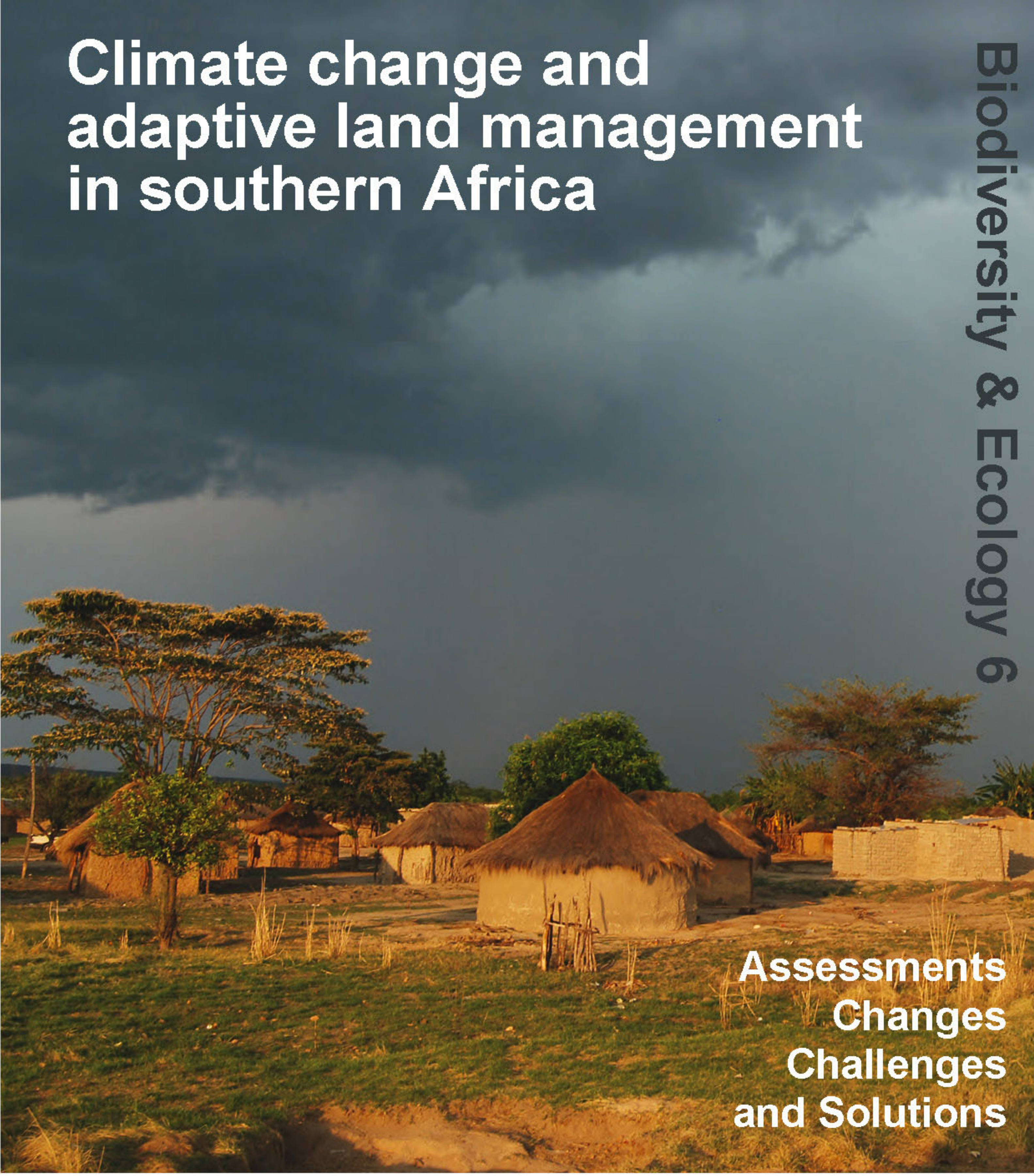

Climate change and adaptive land management in southern Africa

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Acacia trees modify soil water dynamics and the potential groundwater recharge in savanna ecosystems

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Abstract: The effect of increasing tree density on groundwater resources of semiarid landscapes is a topic of controversy. Since 2007, we have registered the soil water dynamics with field monitoring techniques on a commercial rangeland farm in the central Namibian thorn-bush savanna. Monitoring profiles are located below *Acacia mellifera* canopies, in the intercanopy area, and on a de-bushed grassland. Here we demonstrate (1) an increase in soil moisture larger than precipitation at some rain events, interpreted as water run-on resulting from surface ponding; (2) an overall reduction in water infiltration in the below-canopy area of *A. mellifera* compared to the intercanopy space; and (3) a faster drying of the soil in the below-canopy space because of root water uptake. These processes resulted in a potential for deep drainage about threefold larger in the intercanopy space than in the area below the canopy. Thus, increasing bush encroachment is likely to reduce groundwater recharge and should be validated by an interdisciplinary analysis of hydrogeologists, soil scientists, botanists, and farm managers.

Resumo: É controversamente discutido o efeito do aumento da densidade de árvores nos recursos de águas subterrâneas de paisagens semi-áridas. Desde 2007 que registamos as dinâmicas da água no solo, com técnicas de monitorização de campo, numa quinta comercial de pastagens localizada na savana espinhosa da Namíbia central. Perfis de monitorização estão localizados sob copas de *Acacia mellifera*, na área entre copas, e numa pastagem sem vegetação. Aqui demonstramos i) um aumento na humidade do solo maior que a precipitação em alguns eventos de chuva, interpretada como a infiltração de água resultante da sua acumulação à superfície, ii) no total uma reduzida infiltração de água na área abaixo da copa de *A. mellifera*, em comparação com o espaço entre copas, e iii) uma secagem mais rápida do solo no espaço abaixo das copas, devido à captação de água pelas raízes. Estes processos resultaram num potencial de drenagem profundo, cerca de três vezes maior no espaço entre copas que na área abaixo das mesmas. Desta forma, a expansão da invasão do mato poderá reduzir a recarga das águas subterrâneas, devendo ser confirmada por uma análise interdisciplinar de hidrogeólogos, cientistas do solo, botanistas e gestores de quintas.

Introduction

The change in vegetation cover of African savannas, with an increasing abundancy of woody species, is a widely observed phenomenon known as “bush encroachment”. The causes are a subject of debate (Archer, 2010; Briggs et al., 2005; de Klerk, 2004; Eldridge et al., 2011; O’Connor et al., 2014; Van Auken, 2000; Ward, 2005), and neither measures to prevent bush thickening nor generally accepted economic and sustainable strategies to reduce bush coverage have yet been found. The encroachment of bushes has substantial economic impacts on the rangeland farmers, as the capacity of the grazing grounds for livestock is being reduced. The number of livestock in bush-encroached rangelands has thus become much smaller compared to in earlier periods of rangeland management; for example, on commercial farms in Namibia, livestock numbers have decreased since the late 1950s to 36% (de Klerk, 2004).

There has been a long debate about the differences in water consumption of trees and grasses in savanna ecosystems, the competition for water between the two vegetation types in different environmental settings, and the consequences of bush encroachment on water balances and especially groundwater recharge (e.g., O’Connor et al., 2014; Scanlon et al., 2006; Scholes & Archer, 1997). Reviewing the literature on the hydrogeological role of trees in water-limited environments, Lubczynski (2009) summarized that the survival strategy of trees in these systems is typically based on rooting systems that allow water uptake directly from the groundwater or the capillary fringe. For the southern African rangelands, with their widespread bush encroachment, robust information about the interaction of bushes and trees on the one hand and the low layer of grasses, herbs, and dwarf shrubs on the other hand on the water dynamics is limited (Christian, 2010). Thus, SASSCAL studied these interactions with different methodological approaches.

We observed the soil water dynamics of both bush-encroached and debushed areas starting in 2007, using field monitoring techniques on a commercial rangeland farm in the central Namibian thorn-bush savanna, and since 2014 on two additional farms (east of Otjiwarongo, northeast of Grootfontein). The research aimed to understand the influence of different vegetation covers (tree cover versus grass cover) on the processes of infiltration, evapotranspiration, and groundwater recharge. Although groundwater recharge cannot be measured directly (Kinzelbach et al., 2002), the field measurements allow quantification of the number of days per year when deep percolation is physically possible, and thus allow an interpretation of the data with regard to the likelihood of groundwater recharge under various vegetation covers.

Figure 1: Plot EL (12/3/2011); the arrows show the location of the soil profiles “intercanopy” (left) and “below-canopy” (right).

Methods

Study area

The study area is located on a commercial rangeland farm in central Namibia (Otjozondjupa region) about 110 km north of Windhoek. The climate (type BWh, according to Koeppen) is characterized by summer rainfall (predominantly between December and April) with mean annual precipitation of 413 mm (data from local climate station, 2001–2014). Intense rain events often combined with thunderstorms are typical. The high temperature and low humidity lead to a potential evaporation rate of 1,820 mm a^{-1} (Mendelsohn et al., 2009). The topography of the area is almost flat; the altitude, about 1,500 m above sea level. A net of ephemeral river systems of the Omatako catchment drain the farm to the northeast. In the rainy season, the run-off water is retained in dams and swales along the rivers.

On the farm, we monitored soil water dynamics at the two profiles at plots EL (21.654°S/16.686°E) and ES (21.611°S/16.870°E), situated in bush-encroached areas, and at plot EG (21.612°S/16.903°E), located in an area that had been cleared of trees and shrubs. EL was characterized by patches of old *Acacia* trees (Fig. 1) and had a total coverage of shrubs and trees of 12%. ES has a few medium-sized *Acacia* bushes, and the coverage of trees and shrubs is 4.4%. EG was cleared of trees and shrubs by chopping in 2009, and subsequently the soil surface has been ploughed and planted with grasses. EL and ES had a flat terrain, whereas EG was situated in a slight depression. The soils at the studied plots were chromic luvisols; the texture was sandy loam or sandy clay loam for the topsoil, with increasing clay content with depth. With a topsoil pH of 5.1 to 5.5 and low amounts of silt, the soils had low aggregate stability and tended to form surface crusts. At about 1 m depth, the red soil material covered a thin layer of saprolite composed of the bedrock, which is dominated by granites of the Damara granite intrusion. Groundwater depth is about 70 m below the soil surface. Further details on soil properties are provided by Petersen (2008).

Soil water monitoring

Each plot consisted of two instrumented soil profiles. At the bush-encroached plots, one soil profile was situated under a tree canopy and the other soil profile was situated in an intercanopy patch without tree coverage. Both soil profiles at the EG plot were covered with grass, and a tree canopy was absent. The distance between both instrumented soil profiles at each plot was about 5 m.

Soil water content (SWC, % volume) in each profile was monitored using TDR sensors (Easytest type FP/mts, Institute of Agrophysics, Poland) with 100 mm rod length, installed horizontally from an open pit at depths of 20, 40, 60 and 80 cm below soil surface, and which were connected to a logger (type TDR/MUX/mts). The daily measuring interval was fixed at 8:00, 16:00, and 24:00 hours. The sensors additionally recorded the soil temperature.

Soil water storage (SWS, mm) for each profile (1 m depth) was calculated from SWC by taking the respective depth intervals of the four sensors into account. Soil water potential (SWP, pF)

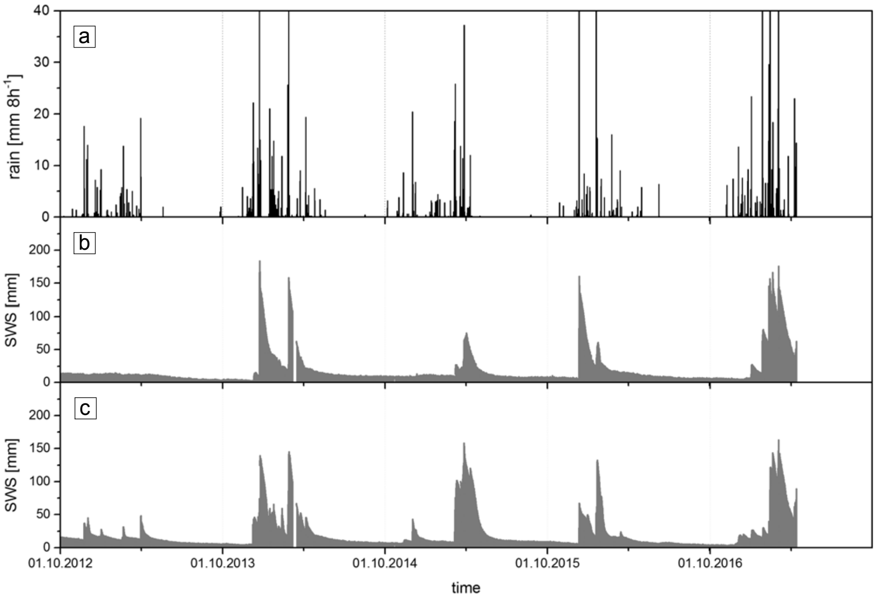

Figure 2: Five years of monitoring of rainfall (a) and soil water storage (SWS) in the below-canopy (b) and intercanopy (c) profiles at plot EL.

was measured with granular matrix sensors (type Watermark 200SS, Irrometer Company Inc., USA) of 22 mm diameter and 83 mm length. The sensors consist of stainless steel electrodes embedded in a defined and consistent internal granular matrix material. The four granular matrix sensors were installed at the same depths as the TDR sensors and connected to a Watermark 900M monitor logger. The logging interval was set to 2 h. The SWP output from the Watermark loggers has been calculated for a predefined soil temperature. We corrected the SWP for the actual soil temperature according to Shock et al. (1998), using the soil temperature measured by the TDR sensors. Significant relationships (field water retention curves) found between measured SWC and SWP were then used to calculate SWP from SWC in periods of missing data. To make inferences on the probability of groundwater recharge, we quantified the number of days per year when deep percolation (i.e., drainage deeper than the deepest sensor at 80 cm) was physically possible (i.e., at SWP ≤ pF 2.5).

Rainfall at each plot was monitored with a tipping bucket (0.2 mm resolution, 15 min logging frequency) in the intercanopy space. Additionally, a SASSCAL climate station has been located on the farm and providing data since November 2010 (www.sasscalweathernet.org; Muche et al., 2018).

At plots EL and ES we monitored soil water dynamics and rainfall for 9 years, from October 2007 to October 2016, and at EG for 5.5 years starting in April 2011, but with roughly 1 year of missing data.

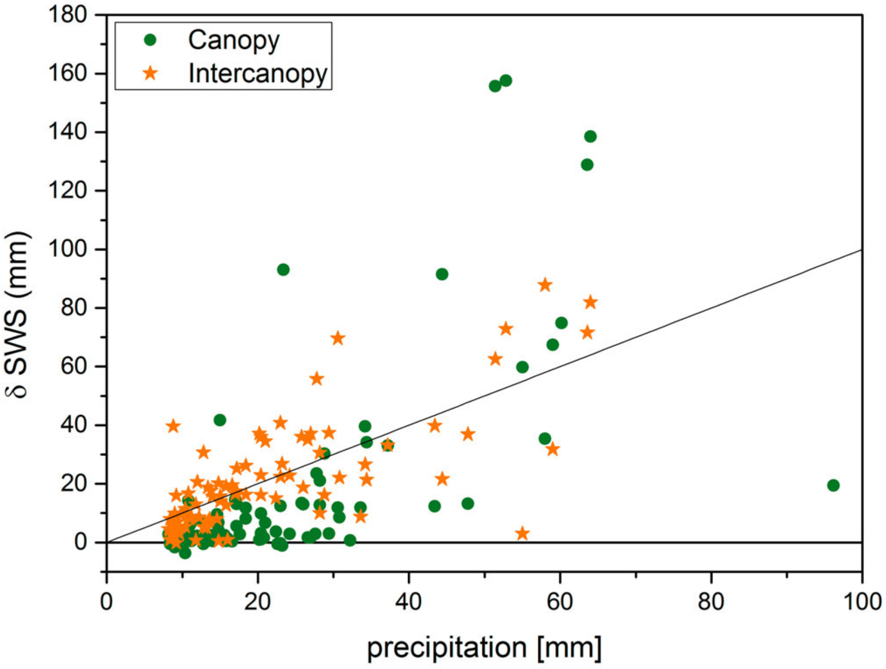

Figure 3: Increase in soil water storage (δ SWS) following rain events (> 8 mm 8h-1) for plot EL (line = 1:1 relation).

Results

The study period was characterized by high inter-annual variability of rainfall. For the 9 years (defined as starting on October 1 and ending on September 30), the mean annual rainfall was 444 mm, varying between 186 mm (2012–2013) and 746 mm (2010–2011). Within the rainy season, the rainfall distribution also varied. Rainfall occurred predominantly between November 20 and April 30, with the long-term maximum monthly rainfall occurring in February.

In relation to the rainfall patterns, highly dynamic water storage in the soils was observed (Fig. 2), controlled by infiltration during stronger precipitation events and the water uptake of plants during the growing season.

Rainwater infiltration

First, we analysed how bushes and trees affect the infiltration of rainwater. To do this we related the rain-induced increase in soil water storage (δ SWS, mm) to the amount of precipitation of all rain events with more than 8 mm precipitation within 8 hours. For smaller rain events, we found no change in soil moisture at all plots and events.

For EL, where the below-canopy profile is located under a large *A. mellifera* patch (see Fig. 1), the relationships between precipitation and δ SWS are shown in Fig. 3. At this plot, we observed that in the intercanopy area:

- rain amounts < 16 mm may not increase soil water content at the first measuring depth (20 cm) and therefore there is also no increase in δ SWS, especially if the soil is initially dry;
- with increasing rain amounts, δ SWS also increases; and
- for some rain events, the increase in soil moisture exceeds the amount of rainfall.

Rain water infiltration below the canopy showed different interactions:

- Even more rain is needed to moisten the soil down to the first sensor (20 cm depth).
- Especially if the soil is initially dry, there is the possibility of a very large increase in soil moisture as a result of rainfall. Here we have registered eight events where δ SWS exceeded the rain amount by a factor of ≥ 1.2 and absolutely by more than 5 mm. As can be seen in Figure 3, the increase in SWS exceeds the rainfall sometimes by a factor of up to nearly four. Of the three most intense rainfalls at this station, two led to the highest observed δ SWS, whereas one event with the highest rainfall amount (2/3/2009, rainfall of 96.2 mm) resulted in a δ SWS of just 19.4 mm.

Although very high infiltration rates have been registered for the below-canopy profile at some events, the sum of all rain events (Tab. 1) shows that the total change in SWS for this profile is 70% of the respective rainfall total, whereas for the intercanopy profile the respective proportion is 100%. For the below-canopy profile, rains with low intensity (< 32 mm) frequently did not lead to increased soil water contents, whereas for the intercanopy profile changes in SWS occurred irrespective of rainfall intensity.

For ES the number of registered rain events was lower (Tab. 2) and the difference between below-canopy (71% infiltration of precipitation) and intercanopy (87%) was not as pronounced as at EL.

For plot EG, the number of analysed rain events was lower than for the other plots. Here, the summed rainwater in-

Table 1: Rainwater infiltration at plot EL – Summary of all events (BC = Below-Canopy; IC = Intercanopy).

Rainfall Class	Number of Rain Events Analysed		Mean Rainfall		Total Rainfall		Total δ SWS		Mean δ SWS		Percentage δ SWS of Rainfall	
	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC
mm			mm	mm	mm	mm	mm	mm	mm	mm	%	%
8–16	52	41	11.7	11.6	605.9	474.8	146.7	419.8	2.8	10.2	24.2	88.4
16–24	18	15	20.2	19.9	363.0	298.8	176.7	373.0	9.8	24.9	48.7	124.8
24–32	13	12	27.8	27.8	361.0	333.4	146.7	391.7	11.3	32.6	40.6	117.5
32–40	5	4	34.3	34.9	171.6	139.4	119.4	90.0	23.9	22.5	69.6	64.6
40–48	3	3	45.2	45.2	135.6	135.6	117.0	98.3	39.0	32.8	86.3	72.5
48–56	3	3	53.1	53.1	159.2	159.2	373.1	138.5	124.4	46.2	234.4	87.0
56–64	5	4	61.0	61.2	304.8	244.6	444.9	273.1	89.0	68.3	146.0	111.7
> 64	1	0	96.2		96.2		19.4		19.4		20.2	
all	100	82			2,197.3	1,785.8	1,543.9	1,784.4			**70.3**	**99.9**

Table 2: Rainwater infiltration at plot ES – Summary of all events (BC = Below-Canopy; IC = Intercanopy).

Rainfall Class	Number of Rain Events Analysed		Mean Rainfall		Total Rainfall		Total δ SWS		Mean δ SWS		Percentage δ SWS of Rainfall	
	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC	BC	IC
mm			mm	mm	mm	mm	mm	mm	mm	mm	%	%
8–16	18	24	11.6	11.6	208.7	278.2	66.2	161.1	3.7	6.7	31.7	57.9
16–24	13	15	19.6	19.5	254.4	291.8	176.9	254.2	13.6	16.9	69.5	87.1
24–32	10	10	26.4	26.4	264.0	264.0	216.2	287.1	21.6	28.7	81.9	108.8
32–40	8	9	36.1	36.4	288.4	327.4	231.7	297.6	29.0	33.1	80.3	90.9
40–48	2	2	43.2	43.2	86.4	86.4	57.1	79.4	28.6	39.7	66.1	91.9
48–56	3	3	52.3	52.3	156.8	156.8	137.2	166.1	45.7	55.4	87.5	105.9
56–64	0	0										
> 64	2	2	88.9	88.9	177.8	177.8	134.5	131.8	67.3	65.9	75.6	74.1
all	56	65			1,436.5	1,582.4	1,019.8	1,377.2			**71.0**	**87.0**

Table 3: Rainwater infiltration at plot EG – Summary of all events (1 = Grass 1; 2 = Grass 2); Frequency of moist subsoil water potentials (SWP).

Rainfall Class	Number of Rain Events Analysed	Mean Rainfall	Total Rainfall	Total δ SWS		Mean δ SWS		Percentage δ SWS of Rainfall	
	1 & 2	1 & 2	1 & 2	1	2	1	2	1	2
mm		mm	mm	mm	mm	mm	mm	%	%
8–16	17	11.5	195.4	324.4	104.8	19.1	6.2	166.0	53.6
16–24	11	19.5	214.2	934.5	198.1	85.0	18.0	436.3	92.5
24–32	3	28.4	85.2	188.1	115.7	62.7	38.6	220.8	135.8
32–40	2	38.2	76.4	151.3	61.1	75.7	30.6	198.0	80.0
40–48	1	47.8	47.8	48.7	35.4	48.7	35.4	101.9	74.1
48–56	1	51.8	51.8	62.7	50.0	62.7	50.0	121.0	96.5
56–64	0								
> 64	0								
all	35		670.8	1,709.7	565.1			**254.9**	**84.2**

filtration differed substantially between the two neighboring profiles (Tab. 3). Whereas for profile 2 the proportion of infiltrated rain was similar to that of the intercanopy profiles of the other plots (84%), for profile 1 the infiltration exceeded the rainfall by a factor of 2.5.

Soil water losses through evapotranspiration

Because of pronounced wet and dry seasons in Namibian savannas and resultant adaptations in vegetation, plant growth is generally low to very low from June to October and high from December to April. This activity pattern is reflected in the soil water storage (Fig. 4). The example of the below-canopy patch of plot EL indicates that daily water losses (δ SWS) by evapotranspiration (ET) may increase in November with the greening vegetation; may further increase until mid-March, when peak rates of ET of 6.8 mm d^{-1} have been measured; and strongly decreases until the end of May.

In general, the daily losses of soil water through root water uptake are controlled by climatic conditions (temperature, vapour pressure deficit (VPD), and wind) and soil moisture availability. Thus, even in the rainy season, low ET has been observed on days with low VPD. During the dry season (from June to October), a much lower ET was observed.

With the reduction of the soil moisture potential, a substantial decline in actual ET has been found for the below-canopy patch of plot EL (Fig. 5). Here, daily δ SWSs of more than 5 mm are restricted to moist soils (SWP < pF 2.4), and at SWP > pF 3, daily δ SWSs are smaller than 1.5 mm.

Compared to the below-canopy profile, in the intercanopy area the reliability of high daily ET on days with moist soils (pF < 2.5) is much less (Fig. 6).

To compare the δ SWS for all profiles, the measured SWPs were put in classes of 0.2 pF width and the distribution of corresponding δ SWS analysed. The daily median δ SWSs for each SWP class (Fig. 7) indicate that under moist conditions (pF < 2.5) the daily soil moisture losses are larger for both below-canopy profiles compared to the respective intercanopy profiles.

Deep percolation

Deep percolation is the outflow of water through the lower boundary of the soil, here defined as a 1 m depth below soil surface. Although no direct measurement of deep percolation is possible, the existing data allow some inferences to be made on this component. The deepest sensors monitoring SWP were installed a depth of 80 cm. The SWP is known to be directly related to the hydraulic conductivity of the soil because as SWP increased, larger pores of the soil become water filled and thus the flow resistance decreases. If SWP gradients exist, water flow is directed from places with high SWP to those with low SWP, typically from moist to dry soil horizons (following matrix potentials) or from topsoil to subsoil (following gravitational potentials). The flow rate (Q) is described by Darcy's law, which says that Q is proportional to the hydraulic conductivity $K(\psi)$ and the potential gradient δ SWP/L.

Table 4: Frequency of moist subsoil water potentials (SWP)

Plot	Profile	Time Period	*n*	Number of Days with SWP ≤ 2.5 pF	Number of Days with SWP ≤ 1.8 pF	Number of Days with SWP ≤ 1.5 pF
ES	IC	10/2007 – 10/2016	3106	594	94	43
	BC		3136	342	23	0
EL	IC		3100	521	150	102
	BC		3121	207	27	8
ES	IC	4/2011 – 10/2016	2005	355	54	36
	BC		2032	149	13	0
EL	IC		2019	317	72	53
	BC		2032	59	0	0
EG	Grass1		2036	416	5	0
	Grass2		2035	259	5	3

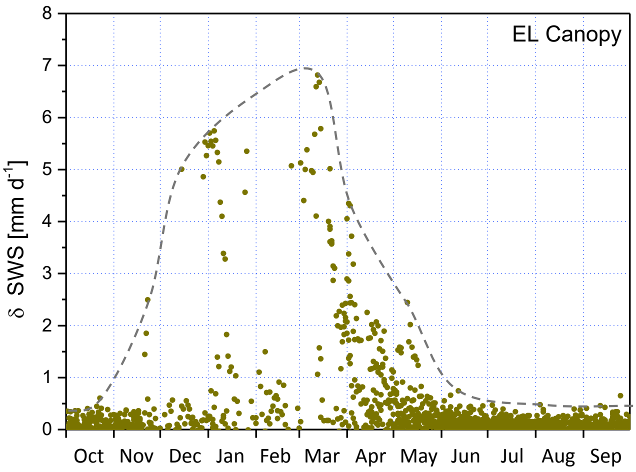

Figure 4: Daily losses of soil water storage (δ SWS) within the season (EL below-canopy). The dotted line indicates the evapotranspiration potential of the vegetation.

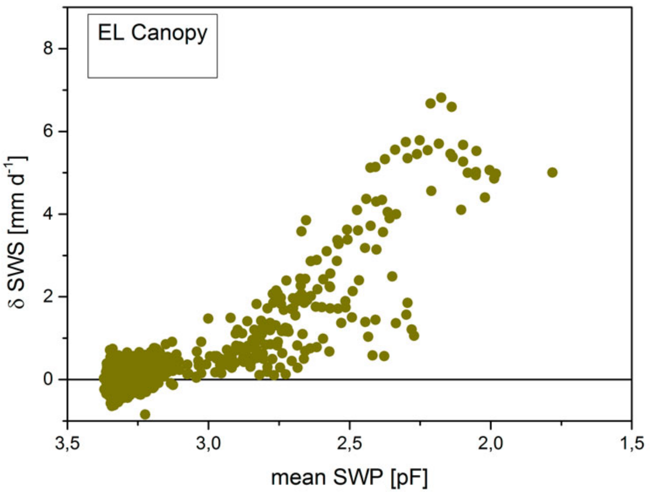

Figure 5: Daily losses of soil water storage (δ SWS) in relation to soil water potential (EL below-canopy).

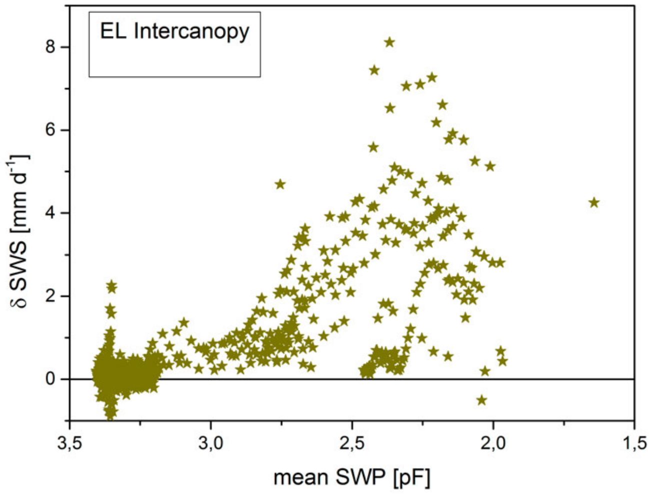

Figure 6: Daily losses of soil water storage (δ SWS) in relation to soil water potential (EL intercanopy).

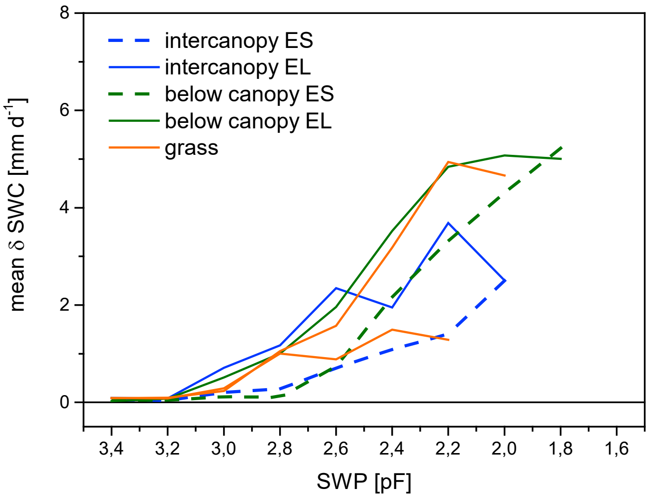

Figure 7: Median of the classified relationship between δ SWS and SWP for all profiles.

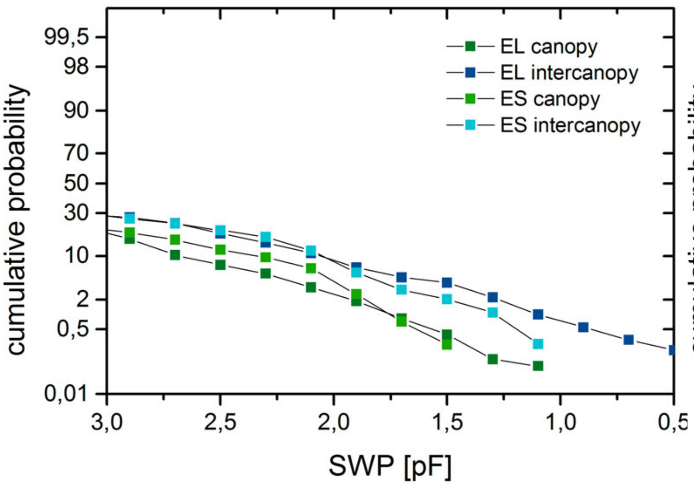

Figure 8: Cumulative probability of SWP at 80 cm depth for the phase Oct. 2007–Oct. 2016. The large proportion of dry subsoils (SWP > pF 3, p > 70 %) is not shown.

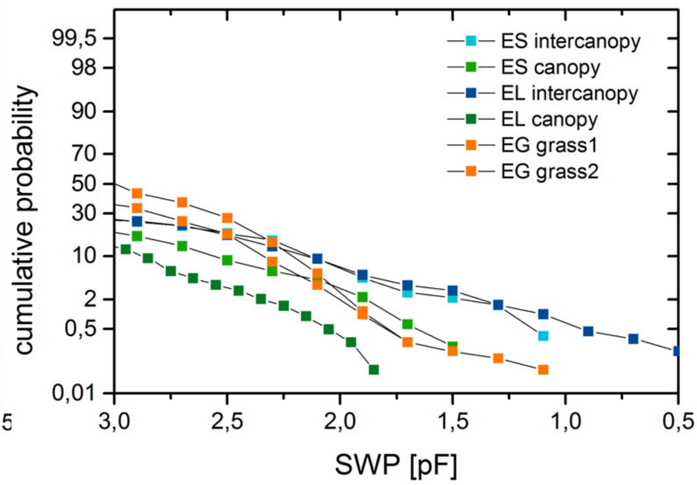

Figure 9: Cumulative probability of SWP in 80 cm depth for the phase April 2011–Oct. 2016. The large proportion of dry subsoils (SWP > pF 3, p > 70 %) is not shown.

Table 5: Weighted probabilities of deep percolation

Plot and Profile	Time Period 10/2007–10/2016	Time Period 4/2011–10/2016
ES – Intercanopy	47.6	40.7
ES – Below-canopy	15.9	15.0
EL – Intercanopy	55.7	42.7
EL – Below-canopy	14.5	2.1
EG – Grass1		13.8
EG – Grass2		10.1

Cumulative probabilities of the SWP for the subsoil (80 cm depth) show that for both bush-encroached plots (EL and ES), the probability of high SWP is significantly larger for the intercanopy profiles than for the below-canopy profiles (Tab. 4, Fig. 8). For example, for the SWP class of 2.0–2.2 pF (centre 2.1 pF), the cumulative probability (p) for the intercanopy profiles is $p = 11.7$ at ES and $p = 11.0$ at EL, whereas for the below-canopy profiles the probabilities are lower: $p = 6.7$ at ES and $p = 3.3$ at EL.

The same type of analysis appears in Figure 9, but restricted to the period of April 2011 to October 2016. This is the period for which simultaneous data from plot EG were available and which consisted of drier seasons. Because of the larger proportion of dry periods, the cumulative probabilities of high SWP are lower compared to the data given in Figure 8. For example, for the SWP class of 2.0–2.2 pF (centre 2.1 pF), the cumulative probabilities for the intercanopy profiles are $p = 9.1$ at ES and $p = 9.2$ at EL, whereas for the below-canopy profiles they are $p = 4.5$ at ES and $p = 0.7$ at EL. Additionally, both profiles on plot EG with grass vegetation show a cumulative probability similar to that of the ES below-canopy profile, with $p = 5.6$ and $p = 3.6$ for pF = 2.1.

To quantify the potential deep percolation, the probabilities of SWP were multiplied by the unsaturated hydraulic conductivity ($K(\psi)$) of the SWP class centre and subsequently summed per probability class (Tab. 5). $K(\psi)$ was derived from laboratory analysis, but restricted to a maximum percolation rate of 10 mm d^{-1}. Because of the increasing $K(\psi)$ with increasing SWP, the difference between the below-canopy profiles and the intercanopy profiles becomes larger. For the total time period (Oct. 2007–Oct. 2016), the probability of deep percolation in the intercanopy space is 3.17 (ES) or 3.84 (EL) times higher than in the below-canopy space. Within the shorter period (April 2011 to Oct. 2016), the probability of deep percolation of both grass profiles at EG is in the range of the ES below-canopy profile and lower than both intercanopy profiles.

Discussion

Reliability of the measured data

In general, the measurement of soil water state properties may be compromised by soil disturbance associated with sensor installation, by systematic errors of the sensors and logging systems, and by particular soil features (e.g., presence of stones) at the measured position. All influences may result in data which are biased and difficult to interpret. We controlled the reliability of the three types of independent automatic devices (rain gauges, soil water content sensors, soil water potential sensors) by assessing (1) relationships between data sets, (2) plausibility checks, and (3) consistency with laboratory data. For the rain gauges, the inter-station comparisons helped to define periods in which individual rain gauges were most likely deficient. For the measurements of SWP, a robust and simple system was applied that was not influenced by the surrounding soil matrix and that showed no signs of long-term trends. SWC was measured with TDR sensors of 100 mm rod length, which were individually calibrated with dry air and pure water before installation. The reliability of SWP and SWC data sets was checked by visual inspection of the “field soil water retention curves” to see whether the shape of the curves reflected typical soil water dynamics. For many soil depth intervals we found a significant relationship between the two independent field measurements, which implied that both types of sensors were able to react to changes in soil moisture simultaneously and in an expected way. From all checks we concluded that, in general, reliable data had been obtained from both types of soil water sensors. We therefore assumed that the unexpected increase in SWC observed at different profiles during some rain events reflected natural processes and was not caused by a malfunction of the sensors. Nevertheless, the necessity of opening a pit to install the sensors and the impossibility of refilling the pit in a way that mimicked the original condition may have caused changes in the soil water dynamics at the pit position. Most likely, this effect was stronger when soil water flows were influenced by preferential flows in macropores and when soil moisture was high.

Impact of bush encroachment on the infiltration process

At all plots, rain events were observed during which increases in SWS (δ SWS) were greater than the measured rainfall amounts (P). One explanation for this phenomenon could be the influence of stemflow from *A. mellifera*. The funnel-shaped and smooth-barked stems of *A. mellifera* are expected to be able to collect rainwater and transfer it to the base of the stem (stemflow; for shrubs of other arid environments, see Martinez-Meza & Whitford, 1996). However, this phenomenon cannot solely explain our observation, since we observed the largest differences at EG, where trees were absent. A more likely explanation is that positive differences between δ SWS and P were related to soil surface run-on to the measuring position at moments of high rainfall. All three positions are almost flat with a topsoil composed of sandy loam (ES, EL) or sandy clay loam (EG). The aggregate stability of the topsoil is low, and under splashing rainfall, the structure tends to break down and form a low-permeable topsoil crust. Ponding water on the soil surface with at least short-distance flows has frequently been observed at the investigation site.

Additionally, inhomogeneous infiltration patterns may be enhanced by preferential flow systems within the soils as produced by shrinkage or the activity of burrowing soil organisms. We observed that immediately after strong rain events, the water content increased rapidly even at a 60 cm depth and concluded that preferential flow phenomena are common in these dense soils. Because of the higher clay content of the soils at plot EG, these flow systems are likely to be more stable there than at the other plots.

Our results show that if the topsoil was dry, it was likely that the sensors in the uppermost depth (20 cm depth) did not show an increase in SWC or SWP, as the rainwater did not reach the 20 cm depth. The precipitation range that registered no response was smallest in the cleared plot (EG) (0–13.5 mm), intermediate in the intercanopy profiles (EL and ES) and the profile below an *A. mellifera* bush (ES) (0–18 mm), and largest under the canopy of a large *A. mellifera* at EL (0–32 mm). This increase in precipitation range with increasing canopy coverage can be attributed to two processes: first, the interception by leaves and branches and subsequent evaporation, and second, the storage of the rainfall proportion reaching the soil surface within the upper soil layer. Here, based on the analysis of the pore distribution, it appears that about 15 to 20 mm of water may be stored in the upper 10 cm of soil.

A summary of the δ SWS of all rain events (> 8 mm 8 h^{-1}) shows a clear reduction of infiltration below larger and smaller canopies (Fig. 10). Under tree canopies, the nine-year cumulative deficit between rainfall and infiltration is 29–33 %. Considering that this proportion is reduced by run-on in the below-canopy area, the deficit may be even larger (e.g., 29–55%) if only the minimum amount of run-on is taken into ac-

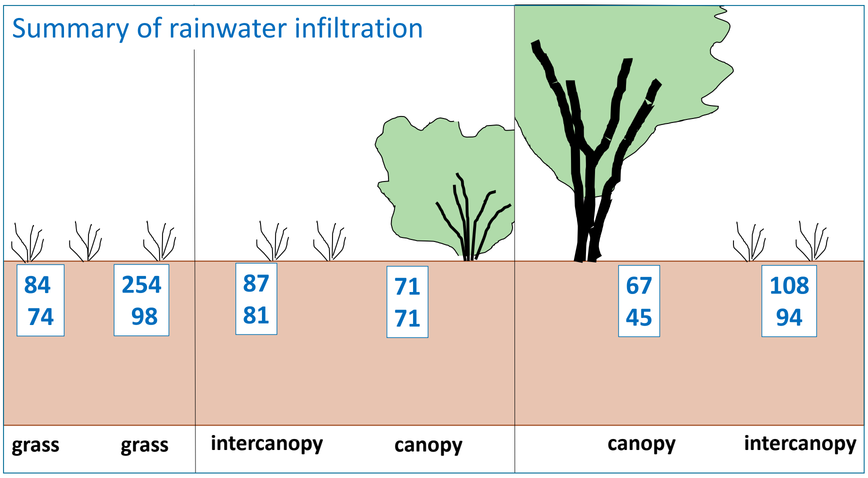

Figure 10: Summary of the proportion of rainfall infiltration (%): Upper value: all events uncorrected. Lower value: all events corrected with lowest estimate of run-on.

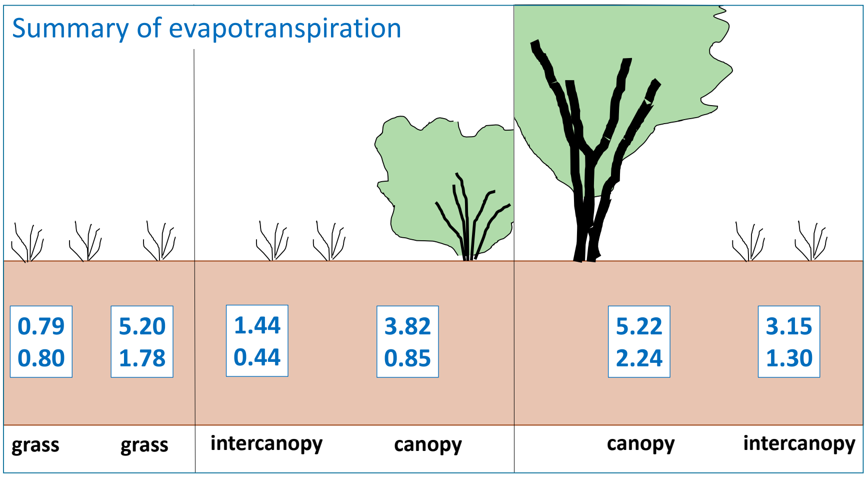

Figure 11: Summary of estimated daily water losses by evapotranspiration (ET, mm d-1): Upper value: median ET for moist soils (pF 1.9 < SWP < pF 2.3); Lower value: median ET for intermediate soils (pF 2.9 < SWP < pF 2.3).

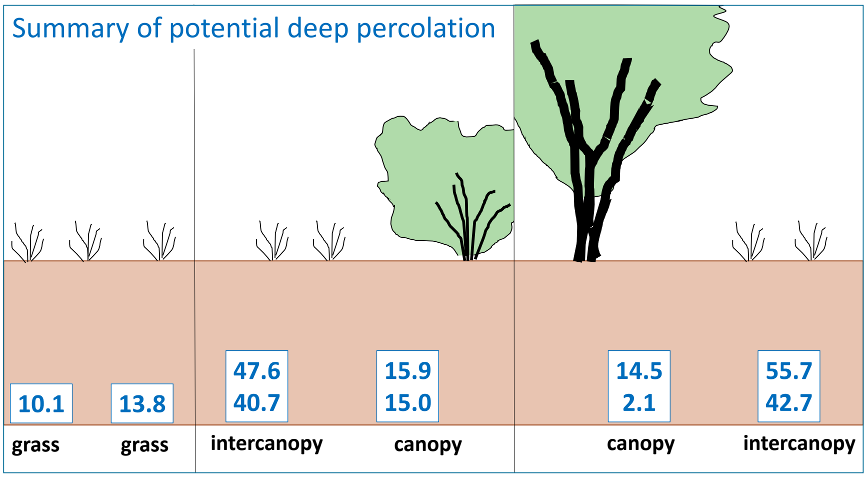

Figure 12: Summary of potential deep percolation. Upper row: weighed percentage for the period Oct. 2007–Oct. 2016; Lower row: weighted percentage for the period April 2011–Oct. 2016.

count. In a two-year study, Belsky et al. (1989) found a reduction of rainfall below canopies of *A. tortilis* and *A. digitata* compared to open grassland on the same order of magnitude (0–50 %). The difference between the rainfall and infiltration amounts may result from interception, which depends on rainfall intensity and duration and may vary in stands of savanna trees between 1 and 5 mm per rain event (De Villiers, 1982). According to Scholes & Walker (1993), however, mean interception is only 2 mm per rain event, an amount that still leaves us with a deficit of about 20% of the mean rainfall. Additional processes that might contribute to the deficit between rainfall and the sum of infiltration and interception are (1) the water storage above the upper soil moisture sensor and (2) stemflow that is not reaching the measurement position. Moreover, run-off could have resulted in reduced infiltration, but this is not very likely given the higher proportion of macropores in the topsoil below trees and the reduction of the raindrop energy through the canopy, both factors that reduce the possibility of run-off from under the canopy to nearby positions.

Impact of bush encroachment on the consumption of soil moisture

We analysed the losses in soil water content (δ SWS) in relation to soil water potential (SWP). These losses are the sum of evaporation and transpiration and possibly deep percolation; as losses were calculated for the whole soil profile up to the depth of 1 m, however, the proportion of evaporation is low and losses might be dominated by transpiration of the plant cover.

In general, there is a strong reduction in evapotranspiration with decreasing soil water availability; at pF 3.0 for all profiles, even the 90th percentile of daily δ SWS is ≤ 1 mm d^{-1} water loss by ET. In the case of moist soils (SWP < pF 2.3), each of the studied vegetation types was able to transpire large amounts of water per day. The 90th percentile for all three types of vegetation cover (trees, intercanopy dwarf shrubs and herbs, grasses) has a maximum of 6.1 to 6.7 mm d^{-1}. However, this potential is most likely realized only in the case of well-developed vegetation stages. Sapflow measurements of *Acacia nigrescens* trees in the Kruger National Park resulted in peak transpiration of 80 mm/month and about 210 mm/year related to the canopy area basis (Dye et al., 2008), which is less than the cumulative water losses that we observe. However, the δ SWS, which is the basis of our calculation, comprises not only tree transpiration but also the transpiration of the below-canopy herbs and soil evaporation. For the intercanopy and one grass profile, the variation in daily water consumption at identical soil moisture conditions is large. In contrast, for the below-canopy profile under a large *A. mellifera* tree at plot EL, the daily water uptake is strongly correlated to the SWP (Fig. 5).

Comparing evaporation under tree canopies with intercanopy patches of ES and EL clearly shows that soil moisture below canopies is consumed at higher daily rates than in the respective intercanopies (Fig. 11). The ratio $\text{ET}_{\text{below-canopy}}/\text{ET}_{\text{intercanopy}}$ varies between 1.7 and 2.7. The absolute values of calculated ET at one of the two grass profiles, however, are the same as the calculated daily ET for the large *A. mellifera* at EL.

The difference in daily ET between below-canopy and intercanopy patches is complicated, however, by the variation in available soil moisture. As rainwater infiltration is less below canopies than in the intercanopy, clear differences in ET are less evident. In addition, the available water below canopies is transpired faster than in the intercanopy area, resulting in greater SWS for the intercanopy profiles, particularly at the end of the rainy season. Focusing on the differences in soil chemical and physical properties below *Acacia raddiana* trees compared to outside grass areas, De Boever et al. (2016) concluded that the trees can positively affect the below-canopy water availability. In our study, the positive physical topsoil properties could not compensate for the reduced amount of infiltrating water.

Impact of bush encroachment on potential deep percolation

As a consequence of differences in infiltration and evapotranspiration amounts between below-canopy and intercanopy patches, the frequency of soil water availability in the subsoil and thus potential deep percolation are altered by presence of trees (Fig. 12). Over the nine-year measurement period of this study, both intercanopy profiles exhibited potential for deep percolation on the order of 3.0 (plot ES) to 3.8 (plot EL) times more than the respective below-canopy profiles. This was the result of both higher infiltration and less evapotranspiration at the intercanopy profiles. The grass plot, which could be compared to the other plots only from 2011 onwards, showed potential for deep percolation that is in the range of the below-canopy profile ES, but larger than that of the below-canopy profile EL. The general difference in the soil-water dynamics between the grass plot and the other two bush-encroached plots is suspected to result from the higher clay content and the thicker soil cover above the bedrock at the grass plot. In general, the lower groundwater recharge below trees is in line with findings from other water-restricted ecosystems (Lubczinsky, 2009), but the magnitude of the role of trees was not reported yet. As roots of *A. mellifera* are known to extend beyond the canopy area, it is likely that the effect of trees on potential deep percolation is even larger than calculated here.

At the intercanopy profile EL, soil water potentials approaching saturation (SWP < pF 1.0) were observed on some days. These values indicate a reduced potential for deep percolation at the lower boundary of the soil profile through the underlying saprolite into the granitic bedrock.

Conclusions

On the plot scale we observed (1) an increase in soil moisture larger than precipitation at some rain events, interpreted as water run-on at moments of surface ponding; (2) in total a reduced infiltration of water in the below-canopy area of *A. mellifera* compared to the intercanopy space; and (3) a more constant and thus faster reduction of soil moisture in the below-canopy space because of root water uptake, which resulted in the potential for deep drainage being approximately three times greater in the intercanopy space in comparison with the below-canopy space. These processes on the local scale are the background to understand hydrological processes on the landscape scale.

Although we found clear impacts on potential deep percolation as a result of the presence of tree canopies, the links between observed soil water dynamics and groundwater level changes remain unknown. At present, the data necessary to study this interrelation are not available, and the measuring infrastructure for groundwater monitoring does not yet exist at the study sites. The relocation of water by surface run-off and run-on, the potential water redistribution by hydraulic lift, and the likely influence of soil organisms such as termites are environmental factors that heighten the complexity of the water dynamics in these water-restricted ecosystems and limit the successful application of hydrological models. To solve the open questions regarding the effects of bush encroachment and de-bushing on groundwater recharge, a larger-scale analysis of groundwater dynamics needs to be combined with (a) soil water monitoring as done in this study, (b) analysis of the water consumption patterns of main encroacher species using sap-flow measurements, and (c) monitoring of the vegetation dynamics.

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