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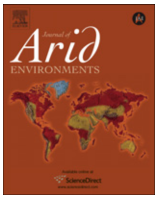

Hydrological implications of desertification: Degradation of South African semi-arid subtropical thicket

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ABSTRACT

Almost half of the 16,942 km^2 of South Africa's subtropical thicket with a substantial *Portulacaria afra* (spekboom) component has been heavily degraded by domestic herbivores. The subtropical thicket biome is a drought-prone and water-stressed area, and many of the region's watersheds comprise of eroded landscapes clothed in degraded spekboom thicket. The objective of this study was to determine the impact of degradation of spekboom thicket on hydrological processes. We hypothesised that degradation of spekboom thicket would reduce infiltration and, hence, reduce soil moisture retention and increase run-off and erosion. We tested this hypothesis by collecting data on rainfall, infiltration, soil moisture retention and run-off in degraded thicket, and – as a reference site – in an adjacent stand of relatively intact thicket. The results showed clear trends in the impacts of spekboom thicket degradation on hydrological processes. The more than hundred-fold lower infiltration in soils associated with degraded thicket relative to the soils beneath the intact, spekboom canopy, resulted in lower levels and less retention of soil moisture, almost double the amount of runoff, and an almost six-fold increase in sediment load. Thus, restoring degraded thicket will reduce erosion and likely improve baseflows, in addition to sequestering carbon.

1. Introduction

While widely acknowledged as being pervasive in most drylands of the world, desertification remains difficult to assess (Verón et al., 2006). A widely accepted definition of desertification is "land degradation in arid, semi-arid and sub-humid areas resulting from various factors, including climatic variations and human activities" (Reynolds and Stafford-Smith, 2002; UNCCD, 1994). This process affects semi-arid shrublands globally, and the severe erosion and flooding that can result has had a high impact on livelihoods (Andreu et al., 1998; Garcia-Ruiz et al., 1996; Thurow, 2000).

Overgrazing by livestock is the most important cause of desertification in South African drylands (Hoffman and Ashwell, 2001; Milton et al., 1994), and subtropical thicket ranks as one of the most extensively livestock-degraded ecosystems in the country (Hoffman and Cowling, 1990; Kerley et al., 1995; Mills and Fey, 2004; Thompson et al., 2009). As opposed to savanna dryland systems, in which livestock-induced degradation often results in shrub encroachment (Higgins et al., 1999; O'Connor, 1994), browsing by livestock in subtropical thicket results in loss of shrub canopy (Lechmere-Oertel et al., 2005a). While restoration will require a reduction in use of the land for livestock production, the provision of other ecosystem services could provide incentive for this (Mills et al., 2005). As observed in other arid shrublands (Andreu et al., 1998; Bautista et al., 2007; Fernandez et al., 2012; O'Farrell et al., 2009), it is predicted that loss of thicket canopy cover will change soil properties and water interactions linked to the provision of water-related ecosystem services, such as local erosion prevention, topsoil maintenance, catchment-scale flood prevention and maintenance of the river baseflow.

South African subtropical thicket is centred on coastal forelands of the Eastern Cape Province. It is a component of the Maputaland-Pondoland-Albany biodiversity hotspot (Steenkamp et al., 2005), and has a high incidence of locally endemic plant species, most of which are succulents (Vlok et al., 2003). While relatively resilient to browsing by indigenous herbivores (Stuart-Hill, 1992), subtropical

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thicket is highly vulnerable to browsing by domestic goats. Sustained, heavy goat browsing can transform the dense, closed-canopy thicket into an open community comprising scattered and degraded thicket clumps and isolated trees in a matrix of ephemeral herbs (Hoffman and Cowling, 1990; Stuart-Hill, 1992; Moolman and Cowling, 1994; Lechmere-Oertel et al., 2005b, 2005a). Particularly vulnerable are drier ($<$450 mm yr^{-1}) forms of thicket (Arid and Valley forms) (Vlok et al., 2003) dominated by the tree-like leaf succulent, *Portulacaria afra* Jacq. (hereafter spekboom). Of the 16,942 km^2 of potentially solid (unbroken canopy) thicket with a substantial spekboom component, 46% has been heavily degraded and 36% moderately degraded by domestic herbivores (Lloyd et al., 2002). Spekboom is the first canopy dominant to succumb to browsing, shows no apparent regeneration once browsing pressure is removed, and is completely eliminated in severe cases of degradation (Lechmere-Oertel et al., 2005a).

The recent emergence of the global carbon economy has provided an unprecedented opportunity to finance the restoration of degraded thicket via carbon credits (Mills et al., 2007, 2010). Spekboom-dominated thicket stores carbon in excess of 200 tons per hectare (measured up to a soil depth of 50 cm), a remarkable feature for a semi-arid ecosystem and comparable to that of mesic forest ecosystems (Mills et al., 2005). Spekboom contributes most of the above-ground carbon to these ecosystems (Lechmere-Oertel et al., 2008; Mills and Cowling, 2006) and its dense canopy provides the relatively cool and dry conditions necessary for the accumulation of the extraordinarily large levels of soil carbon (Cowling and Mills, 2011; Lechmere-Oertel et al., 2005a; Mills and Cowling, 2010; Van der Vyver et al., in press). Research has shown that planting truncheons of spekboom can, after 50 years, result in the return of carbon stocks and community composition to levels comparable to intact, reference sites (Mills and Cowling, 2006; Van der Vyver et al., in press).

While the extent to which degradation of spekboom thicket diminishes the value of ecosystem services such as carbon sequestration, forage for livestock and wildlife, and biodiversity is well understood (Lechmere-Oertel et al., 2005a; Mills et al., 2007; Van der Vyver et al., in press), little is known about the impacts of degradation on hydrological attributes such as water infiltration, soil moisture storage, run-off and erosion. This is an important question since the subtropical thicket biome is a drought-prone and water-stressed area, and many of the region's watersheds consist of eroded landscapes clothed in degraded spekboom thicket. The question then arises: what is the impact of degradation of spekboom thicket on hydrological processes? Answers to this question will enable an initial assessment of the hydrological impacts of the restoration of degraded thicket, which is planned to extend over hundreds of thousands of hectares over the next few decades (Mills et al., 2010). In addition, research that elucidates changes in soil properties and hydrologic status of degraded states provides insights into desertification, the permanence of transformation, and need for active restoration intervention, which the examination of changes in vegetation structure alone cannot do (Dougill et al., 1999).

Based on data from other drylands (Maestre and Cortina, 2004; Sharma, 1998; Thurow, 2000) and laboratory work on thicket soils (Mills and Fey, 2004), we hypothesise that degradation of spekboom thicket would reduce infiltration and, hence, reduce soil moisture retention and increase run-off and erosion. This would happen because, although the dense spekboom canopy of intact thicket would intercept a large portion of the gross rainfall (Cowling and Mills, 2011), the vegetation cover would increase infiltration of water in the soil. The latter trend would be owing to decreased raindrop energy and a greater soil aggregate stability of the more organic-rich soil beneath the canopy compared to soil properties outside the canopy (Lechmere-Oertel et al., 2008; Mills and Cowling, 2010; Mills and Fey, 2004). Consequently runoff would be lower, and moisture retention in the soil profile higher in intact compared to degraded vegetation. We tested this hypothesis by collecting data on rainfall, interception, infiltration, soil moisture retention and runoff in degraded thicket, where the canopy of spekboom and other tall shrubs had been completely removed, and – as a reference site – in an adjacent stand of relatively intact thicket.

2. Methods

2.1. Study site

The study site is located in the Baviaanskloof region of South Africa's Eastern Cape Province (latitude: 33° 35′ 26″; longitude: 24° 08′ 24″) (see Appendix S1 in Supporting Information). Mean annual rainfall is approximately 300 mm and is distributed throughout the year with distinct peaks in spring and autumn (Powell, 2009). The mean annual temperature is 17 °C. Temperatures of up to 40 °C are frequently recorded in mid to late summer whereas winter temperatures may occasionally drop below freezing in valley bottoms. The site comprised a north-facing hillslope with an altitude range of ca. 300 m–500 m above sea level and gradient of 15°. The underlying rocks comprise feldspathic sandstones and shales of the Table Mountain Group. Soils are deep (1–3 m), neutral (pH 7.1–7.3) and moderately fertile sandy loams, with a conspicuous rock component, derived from colluvial weathering of the upslope quartzitic sandstones (Mills and Cowling, 2010). The natural vegetation type is Baviaans Spekboom Thicket (Vlok et al., 2003). In its intact state, the vegetation comprises a continuous 2–3 m high, dense and spiny tangle of multi-stemmed shrubs, low trees and vines. The dominant canopy species is spekboom; woody canopy co-dominants include *Pappea capensis*, *Euclea undulata* and *Schotia latifolia* (Powell, 2009).

The hillslope is bisected by a fence separating two privately owned farms with different management histories that have resulted in a vegetation cover contrast. To the east of the fence, the vegetation is relatively intact, including extensive areas of spekboom-dominated thicket; to the west, the vegetation has been degraded by sustained overgrazing so that no spekboom remains (see Appendix S1 in Supporting Information). Hereafter we refer to these as intact and degraded sites, respectively. Livestock ranching was discontinued in 1979 on the 'intact' site. Although the degraded patches of this site have not recovered – as is the case for all arid forms of thicket (Kerley et al., 1995; Vlok et al., 2003) – patches of spekboom-dominated thicket persist. These properties are bounded in the north by the Baviaanskloof Nature Reserve, which is state-owned and managed by the Eastern Cape Parks and Tourism Agency for nature conservation and water catchment protection. Monitoring equipment was employed on both sides of the fence, within 50 m of the fence on each side, spaced over a total slope length of ca. 400 m.

2.2. Precipitation and interception

Canopy interception was determined indirectly as the difference between gross rainfall and throughfall. We assumed that a fully recovered site will have a closed canopy dominated by spekboom, as observed in intact areas of the same vegetation type within the Baviaanskloof Nature Reserve. Therefore, we considered throughfall measurements made under individual spekboom plants representative of fully recovered spekboom thicket. In the thicket clumps of the intact site, we selected three individual spekboom plants for sampling, which were considered representative of intact thicket in this area. Typical morphometrics taken into account for this selection were: the number of main stems (having a circumference of at least 15 cm), plant height and diameter, and the canopy cover of the plant, which was measured using the binary image method with an upright facing camera (Avsarm and Ayyildiz, 2010). As a result the following selection criteria were used: plants with at least 10 main stems; a height and canopy diameter of ca. 2 m and 3 m respectively; and canopy cover intercepting at least 75% of incoming radiation. We measured throughfall beneath the canopy of the three individuals in two ways: tipping buckets (DFM) with 15 min logging intervals and, adjacent to these, four interception troughs (4 cm wide by 90 cm long) at right angles to each other (Cuartas et al., 2007) (see Appendix S2 in Supporting Information). The latter method captures throughfall beneath a larger area of the canopy than a tipping bucket. To measure the corresponding gross rainfall, we established three tipping buckets on the degraded site at the same altitudes as the monitored spekboom plants. We also installed a conventional rain gauge at the site, which was measured every two weeks for reference. Rainfall and throughfall data were continuously collected. This paper uses the information collected between October 1st 2010 and April 30th 2011.

Although stemflow was expected to be of low importance (Baloutsos et al., 2007; Návar et al., 1999), we did measure it using the approach of Valente et al. (1997). We measured stemflow on one of the spekboom plants and interpolated to make a basic, order of magnitude estimation of this flux. Flows down a single stem were monitored and we scaled up the data using the average relationship between the number of stems and the canopy diameter after the method of Pereira et al. (2009). Measurements were taken between October 1st 2010 and February 20th 2011 using a rubber collar to direct stemflow via rubber tubing into a collecting bucket (see Appendix S2 in Supporting Information).

2.3. Soil profile, infiltration, soil moisture, runoff and soil erosion

We described the soil profiles beneath the spekboom canopy and in the degraded site by excavating soil pits to a depth of 0.6 m at three positions on either side of the fenceline. This included measurement of litter layer thickness and maximum root depth with visual scoring of abundance. We assessed the impact of degradation on the response of soil to rainfall by quantifying the differences in infiltration rate and rewetting patterns in soil beneath the intact spekboom canopy and in the degraded site. We assessed the infiltration rates using a handheld minidisk infiltrometer under moist field conditions (Zhang, 1997). On both sides of the fence, we also measured infiltration at three randomly selected locations. To assess the rewetting patterns we obtained continuous, hourly, capacitance probe measurements of volumetric soil moisture (%) at 0.1 m intervals to a depth of 0.6 m at three locations each at the degraded site and beneath the spekboom canopy at the intact site using DFM Continuous Soil Moisture Probes (Ledieu et al., 1986). Owing to the stoniness of the soil we had to dig the holes instead of using an auger. After the installation of the probe, the pit was backfilled with soil in the layers it was exhumed, and tamped to ensure a good contact between the soil and the device. Soil moisture data were recorded between October 1st 2010 and April 30th 2011. We calculated daily soil moisture volumes using the average soil moisture per depth multiplied by the depth interval.

In addition to these capacitance probe measurements, we installed a total of four TDR (time domain reflectometer) devices in undisturbed soil at representative locations in the degraded and intact sites at a depth of 0.05 m and 0.50 m. The TDR devices were of the type LDM e + SOIL MCT sensor from Eijkelkamp (www.eijkelkamp.com). Soil moisture content (%) was recorded every 30 min between October 13th 2010 and October 31st 2010. In order to assess the accuracy of the soil moisture data thus collected, we used gravimetric methods to determine maximum soil moisture content, i.e. at saturation, of three samples from the degraded and intact sites.

We monitored runoff from October 1st 2010 to February 20th 2011 with Gerlach troughs. Following the approach of Garcia-Ruiz et al. (1996), we located three troughs at the base of the slope, approximately 1 m below a spekboom-dominated thicket clump in the intact site, and three on the same contour in the degraded site. As this study aims to compare the case of complete canopy closure in intact thicket to the degraded condition, we ignored runoff created and preferentially routed in the open spaces between thicket clumps. The hillslope face of the sampled area is not notably concave or convex along a contour and so there was little topographic convergence of flow, and troughs have similar upslope gradients. Some dominant preferential flow paths were obvious in the field on the degraded side and we located troughs to avoid these in order to be conservative in the runoff comparison between sites. Given this field layout, we assumed that the summed catchment area for the three troughs in each site would be of similar size. We recorded the amount of water and sediment in all troughs (degraded and intact) at the end of the monitoring period.

2.4. Statistical analysis

Measurements of phenomena across single, spatially contiguous contrasts are pseudoreplicted (Hurlbert, 1984); hence, we did not apply inferential statistics to assess differences between degraded and intact sites.

3. Results

3.1. Precipitation and interception

Over the three month period (October–December) we recorded 23 rainfall events. However, of these, only 16 events could be used for subsequent analyses (Fig. 1), owing to failure of one or more tipping buckets. Tipping buckets were vandalised by baboons and became clogged with pollen from spekboom blooms during the flowering season. The 16 events (mean = 6 ± (SD) 5 mm) comprised a total of 97 mm gross rainfall, which fell as either a drizzle or as hard downpours with maximum measured intensities of up to 45 mm h^{-1}. Of the total gross rainfall 34% was intercepted by the spekboom canopy and between 1 and 9% was diverted via stemflow. The small rainfall events (<5 mm, together representing 28% of the total gross rainfall) showed the highest interception (55 ± 11%); events larger than 5 mm (representing 72% of the total gross rainfall) registered a lower interception rate of 23 ± 21%. When including all 23 events, gross rainfall comprised 135 mm and interception 41% (Fig. 2). Rainfall intensities beneath the spekboom canopy were considerably lower than those recorded for gross rainfall: the maximum value recorded was 18 mm h^{-1}, during the same rainfall event when the maximum gross intensity (45 mm h^{-1}) was recorded.

3.2. Soil profile, infiltration, soil moisture, runoff and soil erosion

The soil beneath the intact spekboom canopy comprised a dense layer of litter (>5 cm) overlying a stony, black-grey fine sand to a depth of 45 cm, where a stoneline indicated a transition to brown sand. Roots extended to a depth of at least 35 cm. The soil profile in the degraded site lacked a litter layer and had a crust at the surface of the topsoil overlying a brown, chalky loam to a depth of 25 cm,

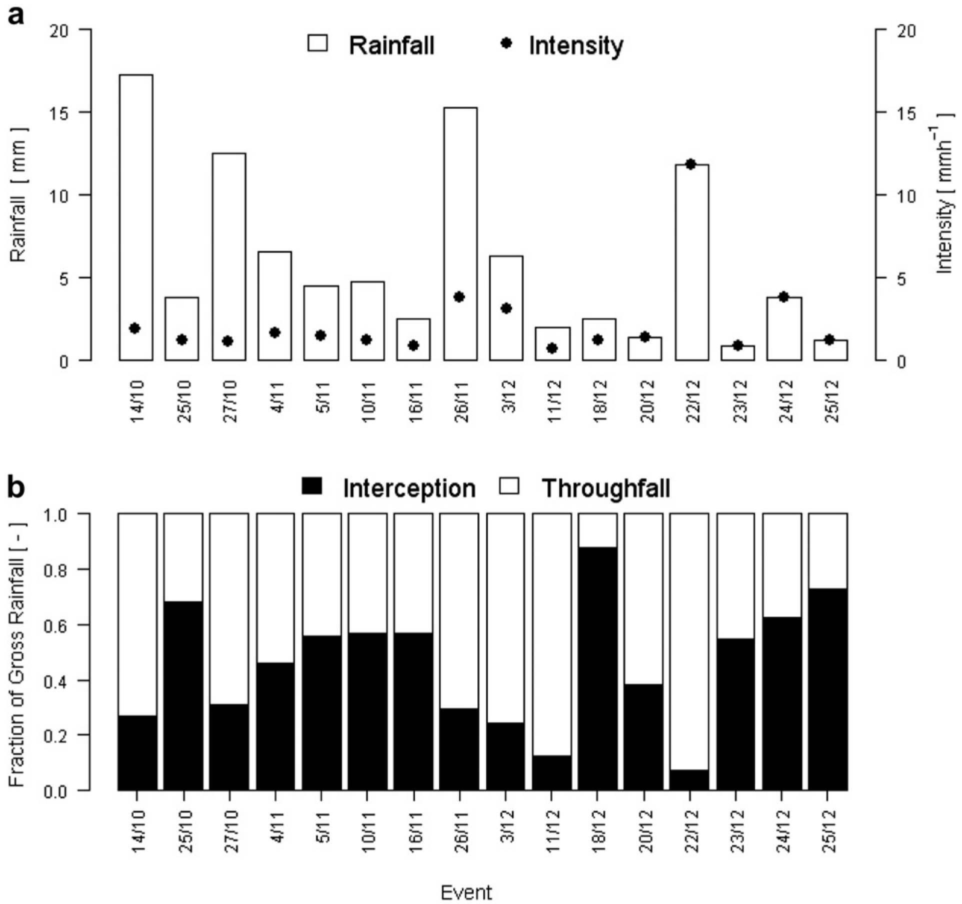

Fig. 1. Rainfall events recorded in the Baviaanskloof (South Africa) study site between October 2010 and January 2011. a) Mean gross rainfall and associated average intensity and b) mean interception and throughfall (including stemflow) beneath the spekboom canopy.

and below that, a rocky, hard and chalky loam of whitish-brown colour. The size and abundance of roots was considerably less than in the soil beneath the spekboom canopy. Roots penetrated to a depth of 30 cm.

The infiltration rate beneath the spekboom canopy varied between 26.1 and 28.7 mm h^{-1}; corresponding data for the degraded soil were 0.04 and 0.25 mm h^{-1}, between 115 and 650 times lower.

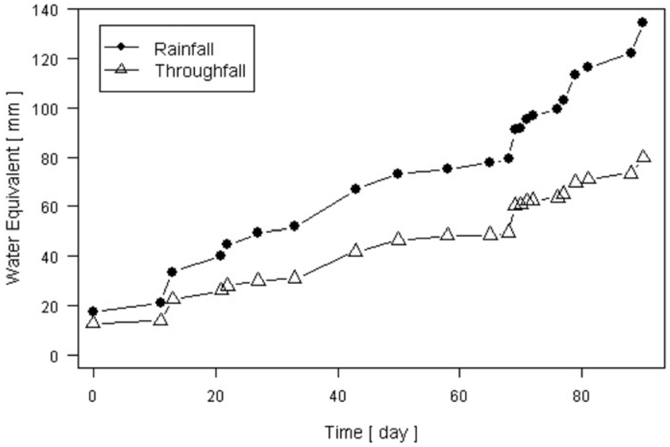

Fig. 2. Cumulative gross rainfall and throughfall measured beneath the spekboom canopy in 23 rainfall events recorded between October 2010 and January 2011 in the Baviaanskloof, South Africa.

Maximum volumetric soil moisture content (at saturation) measured in the lab was 51 ± 5% beneath the spekboom canopy and 37 ± 3% in the degraded site. Soil moisture – as measured using the capacitance probes – mirrored the infiltration rates: higher soil moisture content was recorded over the whole profile in soil beneath the spekboom canopy than in the degraded site soil (Fig. 3). In dry spells the topsoil in the degraded site dried out rapidly and little water was stored in the deeper layers. Elevated soil moisture also persisted for much longer following rainfall events under the spekboom canopy than at the degraded site (Fig. 4). The maximum measured soil moisture (58% in intact site soil and 51% in the degraded site soil) was somewhat higher than the measured maximum soil moisture content. Values recorded using the TDR after a rainfall event in October 2010 (Fig. 5) were more in accordance with lab sample results. The TDR and capacitance probes showed the same patterns of wetting and drying.

Over the three-month monitoring period, we measured 501 L of runoff in the three Gerlach troughs from the degraded site, and 205 L from the intact site, a difference of 59%. Large and intense rainfall events produced the largest differences in runoff between the degraded and intact sites (Fig. 6). The mean sediment load recorded in the troughs located at the degraded site on January 26th, 2011 was 207 ± 118 g whereas that recorded at the spekboom site was 36 ± 33 g, a difference of 83%. There were no substantive differences in grain size of sediments between the two sites. Organic matter content of sediment captured at the degraded site was similar (10.5 ± 0.5%) to that at the intact site (11.4 ± 3.0%).

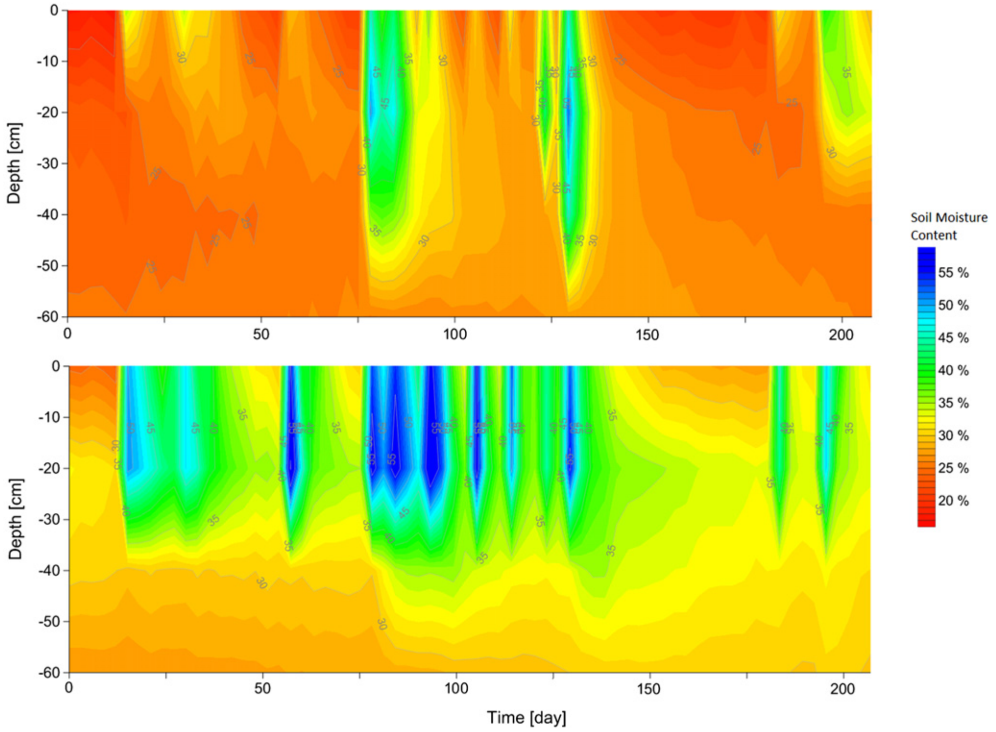

Fig. 3. Depth–time plots of the moisture in the soil profile in degraded thicket (top) and beneath the spekboom canopy (bottom). Data were collected between October 2010 and April 2011 in the Baviaanskloof, South Africa.

4. Discussion

Our data show clear impacts of spekboom thicket degradation on soil properties and associated hydrological processes. The absence of a dense thicket canopy, which intercepts approximately 40% of gross rainfall, results in raindrops of higher kinetic energy striking the degraded site soil. The interception rate of the intact thicket canopy is extraordinarily high for a semi-arid ecosystem. This point has already been made and discussed by Cowling and Mills (2011) who recorded a rate of 43.6% in more mesic spekboom thicket elsewhere in the Baviaanskloof. The high interception rate can be explained by the densely branched and multi-layered nature of the thicket canopy. Where the canopy is lost, the lack of interception, in combination with the lower organic matter content, leading to a reduction of the soil aggregate stability (Mills and Fey, 2004; Thurow, 2000), results in the crust formation and low infiltration rates as observed in this study.

The massively lower infiltration rate in soils associated with the degraded site relative to the soils beneath the intact spekboom canopy (see also Mills and Fey, 2004), results in lower levels and less retention of soil moisture, double the amount of runoff, and almost six-fold increase in sediment load. Similar impacts on soil and hydrological processes have been recorded in other semi-arid shrublands (e.g. Bergkamp, 1998).

The levels of soil moisture recorded in the intact site, and to a lesser extent in the degraded site, are high for a semi-arid

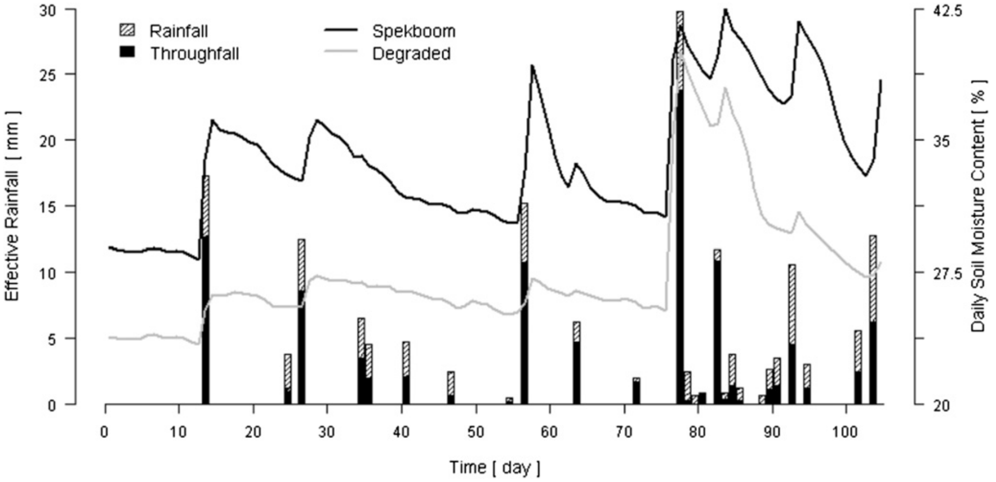

Fig. 4. Soil moisture measurements in relation to rainfall dynamics recorded between October 2010 and January 2011 in the Baviaanskloof, South Africa. Note that after a rainfall event soil moisture increases significantly. In degraded thicket soil moisture decreases quickly afterwards, while in intact thicket soil moisture decreases slowly.

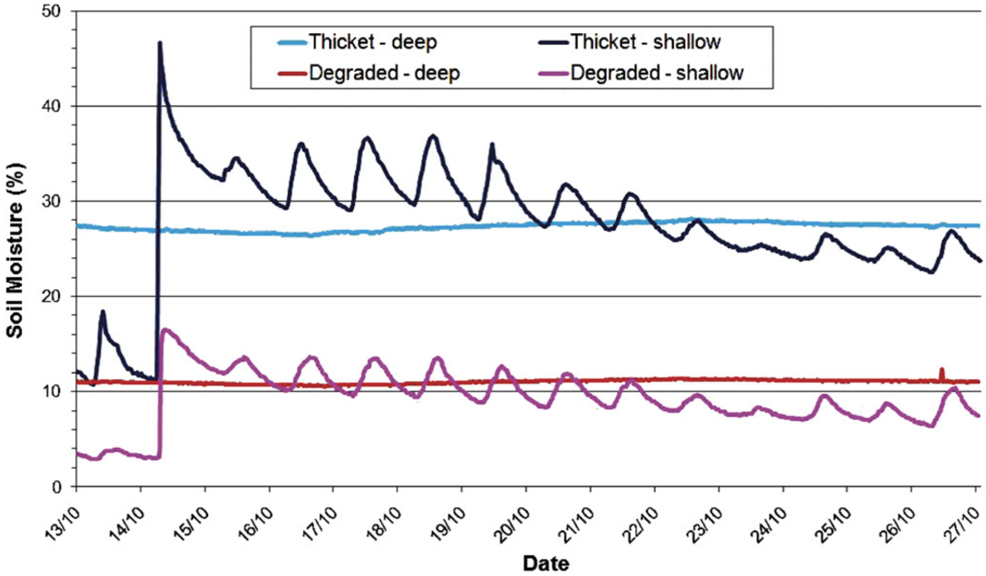

Fig. 5. Soil moisture measurements taken by the TDR soil moisture probes starting before and continuing after a rainfall event on 15 October in the Baviaanskloof, South Africa.

ecosystem, where levels of around 10% are the norm (Martinez-Mena et al., 1998; Paco et al., 2009). These high soil moisture levels, as well as the capacity of spekboom canopy soils to retain soil moisture for extended periods, are most probably a consequence of the extraordinarily high soil organic content in the soil profile and the thick litter layer (de Vries and Simmers, 2002) for such low-rainfall conditions (Mills and Cowling, 2010; Mills et al., 2005). It is commonly accepted that with the increase of organic matter, the water holding capacity of the soil also increases. Reicosky (2005) found that certain types of soil organic matter can hold up to 20 times their weight in water. Hudson (1994) showed that for each 1-percent increase in soil organic matter, the available water holding capacity in the soil increased by 3.7 percent.

Elsewhere in the Baviaanskloof, Mills and Cowling (2010) recorded 104 t ha^{-1} of soil organic carbon in intact thicket, and 45 t ha^{-1} in degraded thicket. While this represents a reduction of more than half, the latter value still exceeds by an order of magnitude values recorded for other semi-arid ecosystems (Mills and Cowling, 2010; Mills et al., 2005). Thus, the surprisingly high soil moisture content of the degraded site may be a legacy of soil carbon enrichment in pre-degradation times.

Stemflow may also play a role in determining soil moisture content beneath the spekboom canopy. Our data showed a wide variation of between 1 and 9%, partly due to technical problems, such as loosening of the rubber collar and an overflowing collection bottle in intense events. These values, however, are comparable with those recorded for desert shrubs by Li et al. (2009), who showed that stemflow, and subsequent movement via root channels, concentrates moisture deep in the soil profile. If anything the technical errors make estimates for spekboom too low, meaning that more water reaches the soil via stemflow than indicated here.

Interestingly, organic content of the sediment loads from intact and degraded sites was similar. Given that litter input in degraded thicket is 90% lower than in the intact state (Lechmere-Oertel et al.,

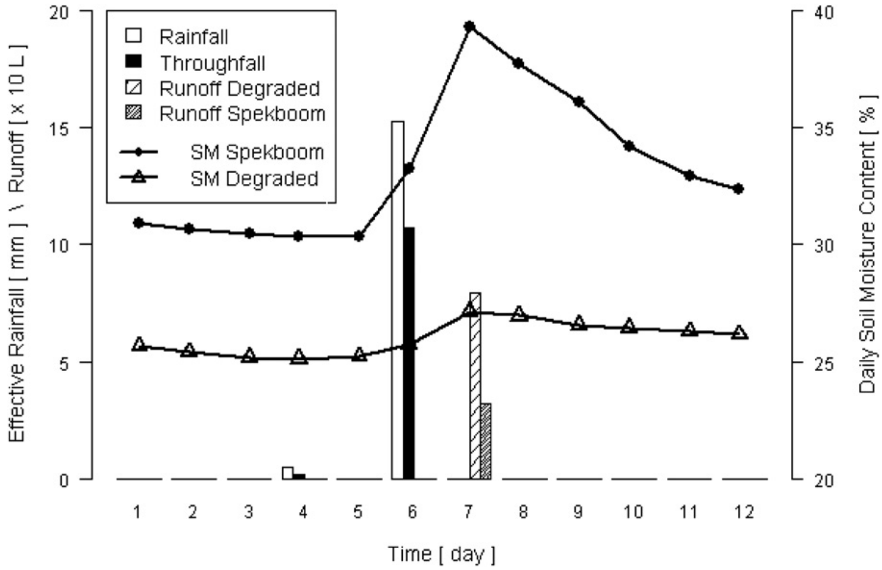

Fig. 6. Runoff, collected in Gerlach troughs located in degraded thicket and downslope of intact thicket, in relation to recorded rainfall and soil moisture after a large rainfall event on November 2011, Baviaanskloof, South Africa.

2008), this implies a steady erosion of organic matter from degraded soils; indeed, belowground carbon stocks of degraded soils are 50–70% lower than those beneath intact thicket (Mills and Cowling, 2010; Mills et al., 2005; Van der Vyver et al., in press). The process we describe is similar to the self-reinforcing cycle of degradation described repeatedly in the desertification literature: reduction in structure and function of vegetation increases soil moisture and nutrient loss which lead to a dysfunctional state incapable of repair without intervention (Dougill et al., 1999; Milton et al., 1994; Sharma, 1998; Thurow, 2000).

Our study has important implications for the restoration of degraded spekboom thicket which is envisaged to be undertaken, via the planting of spekboom truncheons, over several hundred thousand ha in the next few decades (Mills et al., 2010). Restoration will require a reduction in grazing and perhaps exclusion fencing. The services, carbon storage and watershed services, provided by the restored thicket could provide incentives to realise this. Consistent with other research showing that an increase in vegetation cover reduces average annual runoff – and hence water delivery – from catchments (e.g. Le Maitre et al., 2002; Lu et al., 2012; Wilcox et al., 2006), our results show that restoring a spekboom canopy is likely to result in less runoff than that from degraded catchments. This is because gross rainfall is intercepted by vegetation, while at the same time plants uses large quantities of water, which returns to the atmosphere by means of transpiration.

However, restoring spekboom thicket could increase baseflow by increasing infiltration and hence, subsurface contributions to streamflow (Price, 2011). Furthermore, runoff peaks will also decrease as a result of restoration, causing in significant reduction in erosion rates (Garcia-Ruiz et al., 1996). It is important to bear in mind when considering the impacts of restoration of plant cover on hydrological processes, that while the overall runoff of a system is important, seasonally sustained flow of high quality water in rivers is also significant. Restoration of degraded thicket catchment could improve long-term yields of water to supply dams by evening out inflow hydrographs, reducing spillage loses, and by reducing dam sedimentation (Blignaut et al., 2008; Manders et al., 2010). Consequently, unlike the case for tree plantations, we do not anticipate a trade-off between carbon sequestration and water yield in the restoration of spekboom thicket (Jackson et al., 2005).

We acknowledge several flaws in the study and it should be regarded as preliminary in some respects. Firstly, the design is pseudo-replicated; we cannot say with any level of statistical certainty whether we have measured a degradation effect or a site effect. The latter seems unlikely given the proximity of the two sites (Appendix S1 in Supporting Information). However, future research should endeavour to include at least three replicate contrasts. Future research should also include sites of different post-restoration age. These are becoming available as the restoration program gathers momentum. We further recommend that a comprehensive water balance approach (Allen et al., 1998) is adopted. This will require, in addition to the hydrological attributes we measured, data on potential evapotranspiration. Finally, the experimental sites should be subject to long-term monitoring of streamflows, baseflows and sediment loads.

5. Conclusion

This study clearly demonstrates notable hydrologic impacts of the loss of spekboom thicket canopy cover. Comparing measurements in a grazed area without a thicket canopy to those in an area with intact thicket cover on the same hillslope, separated by a fenceline, it was found that the loss of thicket cover had resulted in an extreme change in soil infiltration rates, a decrease in soil moisture retention, an increase in run-off, and increase in erosion. Despite the relatively high rainfall interception rate (roughly 40%) observed for spekboom thicket, the differences in infiltration more than compensated, leading to greater soil moisture beneath intact thicket. The change in soil properties and hydrologic response indicates the relative permanence of this degradation – and, hence, the need for active restoration. These results compare well to studies in semi-arid shrublands (Bergkamp, 1998; Maestre and Cortina, 2004; Sharma, 1998; Thurow, 2000) and demonstrate local water-linked ecosystem services associated with spekboom thicket restoration, such as preventing erosion and lowering storm run-off peaks. Increased infiltration may also result in increased baseflow if some of the retained water is later released. However, more research is needed to confirm this. Such benefits, as well as carbon sequestration, could provide help to provide the incentives needed to support restoration activities.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2012.10.022.

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