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THE ECOLOGICAL AND FINANCIAL IMPACT OF SOIL EROSION AND ITS CONTROL – A CASE STUDY FROM THE SEMIARID NORTHERN CAPE PROVINCE, SOUTH AFRICA

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ABSTRACT

We analysed the extent of ecological damage of gully and inter-gully erosion in a sub-catchment situated in the drylands (300 mm yr^{-1}) of the winter rainfall area of South Africa where small-stock farming on rangeland is the main source of income. We applied low-cost measures to revegetate the bare sites of the inter-gully erosion and stabilised gully erosion by loosening soil surfaces and applying geotextile and constructing check dams to reverse gully erosion. We compared vegetation cover, silt accumulation and penetration resistance of the soil upslope of the check dams with the situation downslope of the check dams and untreated gullies as controls. For the treated bare patches, we compared penetration resistance and vegetation cover with untreated controls. Two years after implementation, the restoration measures resulted in increased soil depth and vegetation cover upslope of the check dams and increased vegetation cover on the treated bare patches. We calculated the net present value of the restoration measures based on the financial benefit that a landowner can realistically expect under current economic and governance conditions (i.e. payment for additional livestock and for C sequestration). At the current rates of return for livestock production or carbon sequestration over a 20-year period, rehabilitation of this sort is not financially feasible for private landowners. Either the current payment for carbon sequestration would have to be increased by a magnitude of 40–80, or restoration measures would have to be funded by the public or private sector to make them financially viable for landowners. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: bare-patch restoration; carbon loss; carbon sequestration; check dams; low-cost restoration

INTRODUCTION

Soil forms the interface between Earth's lithosphere, hydrosphere, biosphere and atmosphere and in this function provides key provisioning, regulating, supporting and even cultural ecosystem services (Brevik *et al*., 2015; Adhikari & Hartemink, 2016). Irrespective of the high ecological and economic value of soil, accelerated soil erosion, one of the world's greatest environmental and agricultural challenges (Pimentel, 2006), leads to loss of fertile topsoil and land degradation (MEA, 2005). The main drivers of accelerated erosion are inappropriate soil management (Cerda *et al*., 2009; Olang *et al*., 2014; Keesstra *et al*., 2016) and infrastructure measures (Seutloali & Beckedahl, 2015) that lead to loss of vegetation cover and excessive surface water flow. Vegetation cover (Lieskovsky & Kenderessy, 2014) but also plant species diversity (Berendse *et al*., 2015) and plant root structure (Ola *et al*., 2015) play an important yet often underestimated role for the control of soil erosion. Drylands with low productivity are particularly threatened by degradation and soil erosion. South Africa, where about 96% of the land surface has been classified as dryland (Hoffman & Ashwell, 2001), experiences a mean annual loss of topsoil of 3 Mg ha^{-1} through water erosion (O'Farrell *et al*., 2009). Along with the topsoil, water holding capacity, essential plant nutrients, soil organic matter and soil biota are also lost (Lal, 2001; Dregne, 2002; Pimentel, 2006). In view of the growing demand for sustainable and fertile agriculture caused by the pressure exerted by the growing world population and globalisation, efforts are needed to avoid further degradation of rangelands and fields and to restore and re-cultivate degraded lands for food production (Lal, 2001).

Landowners are often prepared to restore degraded lands for a variety of reasons that include non-monetary benefits that are expected to improve their livelihoods in the long term (Weston *et al*., 2015). Restoration, particularly of degraded drylands, is a slow process because of the low productivity and the low monetary return of drylands, which makes their restoration economically challenging (Milton, 2001; Herling *et al*., 2009). Costs and monetary returns of dryland restoration measures are generally poorly recorded (Herling *et al*., 2009), which makes the evaluation of the economic success of restoration very difficult (Bullock *et al*., 2011). This is particularly true regarding the returns from improved ecosystem services, which are seldom referred to in detail (Blignaut *et al*., 2013). A few studies from South Africa indeed show that restoration measures could be cost-effective if society appreciates and pays for the services that these ecosystems provide (Mills *et al*., 2013; Mills & Cowling, 2014).

With this case study, we contribute another piece to the puzzle. We assess the ecological damage (i.e. loss of

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grazing, soil and carbon) caused by gully and inter-gully erosion over a period of 50 years in a catchment of 33·6 ha in semiarid South Africa and analyse the ecological effect of the restoration 2 years after implementation. Finally, we calculate the net present value (NPV) of the restoration measures based on the realistically achievable additional income due to restoration.

MATERIAL AND METHODS

Study Area

The study site is a sub-catchment on the farm Avontuur (31°15′37″S, 19°04′04″E) on the Bokkeveld Plateau of South Africa. The 1300-ha farm is located in the Namakwa District of the Northern Cape Province, 15 km north of the town Nieuwoudtville. With a mean annual rainfall of 300 mm, which mainly falls during the winter months, the area is classified as semiarid (Oettlé, unpublished data). The landscape is moderately undulated; the average steepness of the slope within the sub-catchment is around 6·5%. The clayey silty soils of about 50 cm depth are derived from the shales of Dwyka Tillite, which host the distinct vegetation type of Nieuwoudtville Shale Renosterveld of the Fynbos Biome (Mucina & Rutherford, 2006). The main sources of livelihoods in the area are livestock farming for meat and wool production as well as indigenous Rooibos tea production, the latter produced exclusively on soils derived from the adjacent Table Mountain Sandstone.

The area was settled around 1750 and, since that time, has been intensively grazed in all seasons of the year. This resulted in loss of vegetative cover and soil erosion in a number of steeper areas of the catchment, which are recognisable by the extensive occurrence of lichens on the soil surface and the age of shrubs, estimated to be more than 50 years. However, the majority of the damage was caused in the post-WWII period by ploughing with mould-board ploughs. Severe surface run-off, which originated from bare (vegetation-free) patches or man-made channels, has promoted gully formation and inter-gully erosion at the study site with a considerable loss of fertile soil (Oettlé, unpublished data).

In 2008, the farmland was purchased by the World Wide Fund for Nature South Africa to conserve its unique biodiversity and to restore erosion damage. Between April and August 2011, soil and water conservation measures (i.e. gulley check-dams and bare-patch treatments, see succeeding text for details) were implemented on a section of the property with badly eroded soils in an attempt to control the gully erosion, enhance retention of rain water, promote revegetation and halt or even reverse the processes of land degradation.

Assessment of Soil Erosion and Soil Carbon Loss

The boundary and the size of the restored sub-catchment area were determined based on the contour lines of the surrounding elevations provided by Google maps (Google Inc.; https://maps.google.de/; accessed 23·08.2013). The extent of the gully system was mapped with a portable GPS device (GPSMAP 76CSx), which recorded the GPS track at a constant height above the soil surface, while we walked along the floor of each gully at the study site. The tracks were mapped using the software 'Quantum-GIS' (QGIS Development Team; Version: 1·8.0). To calculate the volume of the eroded soil material within the study site, we recorded the depth and the width of each gully at 20 m intervals along the entire course of all gullies and determined whether the shape of the cross sections was elliptic or rectangular and calculated the volume of the eroded soil according to the shape (Figure S1). If the shape of the cross section changed at shorter intervals than 20 m, the measurements were taken more frequently. The total gully volume resulted from the sum of the single section volumes.

The area affected by loss of plant cover ('bare patches') was determined through visual inspection of the Google Earth satellite images (dated 14·09·2011). The total size of the area was assessed in the Quantum-GIS. Inter-gully erosion at bare patches was estimated by visual onsite inspection. Figures for soil mass and carbon (C) stock were taken from Mills & Fey (2004), who calculated a soil C content of 65 Mg C ha^{-1} based on a mean bulk density of 1·5 Mg m^{-3} and a soil depth of 50 cm for Renosterveld on Dwyka Tillite soils in the direct vicinity of our study site. The amount of soil C lost through a 10 cm layer of inter-gully erosion was also based on Mills & Fey (2004), who showed that the upper 10 cm soil layer has a C content three times higher than the lower soil horizons.

Assessment of Biomass and Plant Carbon Loss

Because of overgrazing and soil disturbance in the past, the vegetation of the sub-catchment consists predominantly of monodominant stands of the two shrub species: renosterbos (*Dicerothamnus rhinocerotis* (L.f.) Koekemoer, Asteraceae) and kraalbos (*Galenia africana* L., Aizoaceae). We estimated the total area of the study site covered by renosterbos or kraalbos, respectively. For each of the two vegetation types, we estimated the vegetation cover per area (5 m^2) in percent as projected from a bird's eye view of the soil surface and determined the mean number of adult individuals per 1 m^2. The aboveground standing biomass of the study site was calculated based on allometric measurements for these two species. The plants' aboveground volumes were assessed using the approach described by Anderson *et al.* (2010). We measured the height and two diameters (i.e. first diameter at the widest part and the second diameter perpendicular to the first) of five randomly selected adult shrubs per species and calculated the aboveground standing biomass (fresh and dry) by applying the species-specific volume-biomass regressions established by Anderson *et al.* (2010) for the two species (Table S2). The authors established the regressions from plants in the Kamiesberg area in the Upland Succulent Karoo vegetation under similar rainfall conditions, about 150 km north-west of our study site. We calculated the total fresh and dry aboveground biomass (in kg m^{-2}) per species and study site based on the species' density (plant m^{-2}) in the monodominant stands and the relative share of these stands of the entire study site. Dry

Table I. Assessment of the biotic and abiotic variables regarding effects for check dams and for geotextile on bare patches

Variable	Measurements for check dam effects per 0·25 m^2 (50 cm × 50 cm)	Measurements for geotextile effects on bare patches per 0·25 m^2 (50 cm × 50 cm)
Abiotic variables		
Penetration resistance	5x within the plot (in each corner and in the centre); mechanical penetrometer (Eijkelkamp): 0–4·5 MPa	5x within the plot (in each corner and in the centre), mechanical penetrometer (Eijkelkamp): 0–4·5 MPa
Soil depth	5x within the plot (in each corner and in the centre); probed with a metal rod hammered into the ground	Not applicable
Biotic variables		
Total vegetation cover	Cover in percentage (live + dead material standing and litter)	Cover in percentage (live + dead material standing and litter)
Live plants		
Grass, annual dicots, herbaceous and woody perennials	Cover in percentage per plant type	Cover in percentage per plant type
Dead plants		
Grass, herbaceous and woody perennials	Cover in percentage per plant type	Cover in percentage per plant type
Litter (dead organic material covering the soil surface)		
Grass, woody perennials	Cover in percentage	Cover in percentage
Mammal droppings	Not applicable	Abundance (counts)

aboveground biomass was converted into C content, using the conversion factor of 0·5 (Pettersen, 1984). Root C stock was taken from (Mills *et al.*, 2013) who assessed belowground plant C for fallow fields covered by Renosterveld vegetation in the southern Cape (Overberg region) with slightly higher rainfall (400 mm p yr^{-1}) as being at 4·0 Mg C ha^{-1}.

Restoration Measures and Their Effects

The check dams were constructed in the winter months (April–August) of the year 2011 from rocks, wooden poles, geotextile and brush. The wooden poles were largely produced by clearing alien tree stands (pine and poplar species) elsewhere on the property and were placed horizontally across the gullies at intervals of between 10 to 20 m. Pieces of geotextile (Soil Saver 292 ®, 100% natural jute fibres from Kaytech, South Africa) of about 1·20 m × 2 m in size were folded over the poles and secured on the upstream side by weighing them down with stones and soil to prevent them from being washed out by run-off water. These structures were then bolstered by packing rocks below the check dams. To further calm the flow of the run-off water and promote infiltration, brush packs using the branches of shrubs from the farm secured by rocks were placed on the upstream side of the check dams. An intended effect of these check dams was to filter the run-off water, retaining most silt, seed and organic material behind the geotextile and within the brush packs.

The bare patches were restored by loosening the exposed subsoil with a pickaxe to a depth of approximately 15 cm. Organic material (sawdust of *Pinus* spp.) and seed-rich topsoil taken from the site was introduced and the surface subsequently covered by the same geotextile as used for the check dams. The geotextile was secured by weighing the edges down with rocks from the surrounding farmland.

The restoration effects were sampled in March and April 2013. For the check dams, we measured the abiotic and biotic variables listed in Table I within 50 cm × 50 cm plots placed at 1-m upslope and downslope of the check dam (Figure 1, Figure S2). Every second check dam along the gullies was assessed; if one of the check dams was visibly damaged, it was omitted and the next functional one was

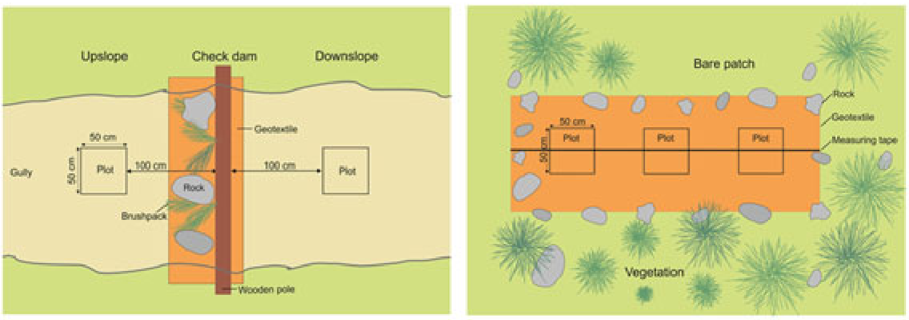

Figure 1. Position of the 50 cm × 50 cm plots placed at 100 cm upslope and downslope of the check dam (left) and sampling design for treated bare patches. Plots were placed in equal distance to the bare-patch edges and each other (right). See text for further details. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

chosen instead. As controls, we selected untreated gullies within the study site where we conducted the same measurements of abiotic and biotic variables and noted the same accompanying information as for the check dams. The sample size per group was $n = 20$.

Of the treated bare patches and their untreated controls ($n = 10$ per treatment and control, respectively), the longest length and broadest width of the patch was recorded. Along the longest diameter of the bare patch, three plots of 50 cm × 50 cm in size were placed at equal distance from the edges and from each other. For each of the plots, the biotic and abiotic variables were assessed following a similar approach as for the plots on the gully floors at the check dams (Table I). In addition, the droppings of mammals per plot were counted as an indicator for the attractiveness of the restored patches for the wildlife.

The visual inspection of normal distribution and all statistical analyses of data was conducted with the software programme PAST (Version 2·17c). For the gully treatments, we analysed the variances between the values for soil depth at the gully floor, penetration resistance of soil surface, and for cover values per functional plant type for all three sample groups (upslope, downslope and control). Because of a lack of normal distribution of the data, we applied the Kruskal–Wallis non-parametric ANOVA using the median of the rank-sums to compare the three independent samples and applied a Mann–Whitney pairwise comparison to identify which pairs differed, if applicable. As a conservative correction for multiple testing, we used the Bonferroni correction. The association between bare-patch treatment and presence of dung was tested by Fisher's Exact Test (Agresti, 1992). Because the data were not normally distributed, we applied the Mann–Whitney U test to compare the effects of the treatments on the abiotic and biotic variables.

Assessment of Cost and Benefit of Restoration

The cost for the restoration treatments was compiled based on Oettlé (unpublished data), who conducted the restoration. For the financial cost and benefit assessment, we applied a simple NPV calculation

$$NPV = \sum_{i=1}^{20} \frac{(B_i - C_i)}{(1+d)^{i-1}}$$

where NPV is the net present value over 20 years (ZAR), B_i is the benefit in year i (ZAR), C_i is the cost in year i (ZAR) and d is the discount rate of 0·05, which was used based on current

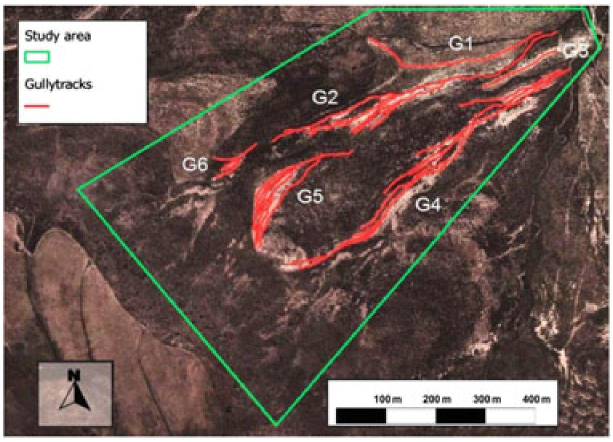

Figure 2. Map of the gully systems within the study site. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

discount rates at South African commercial banks. Restoration costs have been calculated in South African Rand (ZAR).

Cost of vegetation degradation and soil erosion was calculated based on the productivity loss approach (Marta-Pedroso *et al.*, 2007; Galati *et al.*, 2015). The productivity loss approach calculates the productivity loss in terms of reduced yield as a measure for the monetary costs of erosion by calculating the productivity loss per degraded area in terms of small livestock (sheep). The recommended stocking rate for the study area ranges between 4 and 7 ha SSU^{-1} (NO, unpublished data). The income from livestock was calculated based on the selling price of 50 ZAR kg^{-1} for an A2/3 lamb (RPO RMPO, 2014). Based on a previous study (Mills *et al.*, 2013), we assumed that a resting phase of at least 10 years is required for vegetation recovery before the recommended stocking rate can be applied. The applied C sequestration rate for our study site was based on figures provided by Mills *et al.* (2013). The authors calculated C sequestration rate of 0·5–1·3 Mg C ha^{-1} yr^{-1} for fields that have been fallow for 10–25 years in Renosterveld with an annual average rainfall of 400 mm. Our study site receives lower annual rainfall (300 mm yr^{-1}); we therefore considered the lower end of the range (0·5 Mg C ha^{-1} yr^{-1}, equalling 1·9 Mg CO_2e ha^{-1} yr^{-1}) as an adequate assumption. For the average C prices on the global market we used 75 ZAR (i.e. \$5, voluntary market) and ZAR 150 (i.e. \$10, compliance market) for 1 Mg CO_2e for the year 2013 following (Goldstein *et al.*, 2014), based on an exchange rate of \$1 = ZAR 15.

Table II. Extent of gully erosion (sum of the length of all side arms) and the number of side arms for each system

Gully ID	Number of side arms	Length [m]	Volume [m^3]	Surface area [m^2]	Soil loss per gully metre [m^3 m^{-1}]
G1	1	295·00	36·57	217	0·12
G2	8	1,315·00	735·82	2,225	0·56
G3	1	146·00	33·50	173	0·23
G4	10	1,520·00	1,796·95	3,426	1·18
G5	10	944·00	640·06	1,853	0·68
G6	4	195·00	76·75	270	0·39
Total	34	4,415·00	3,319·65	8,164	
Mean	4·87	735·83	553·28	1,360	0·75

Table III. Calculated total carbon loss from the study site (33·6 ha) through vegetation and soil loss and literature source for the C stock

Type of C stock	Total C (in Mg)	Source
Soil C	443·0	Mills & Fey (2004)
Aboveground plant C	45·6	Anderson *et al.* (2010)
Belowground plant C	40·0	Mills *et al.* (2013)
Total	528·6	

RESULTS

Extent of Soil and Carbon Loss

The sub-catchment that demarcated the study site covered an area of 33·6 ha. The gully systems comprised six partly connected gullies of different length and volume (Figure 2). The total length of all gullies was 4·415 m (Table II) and resulted in a total loss of 3·320 m^3 soil material, equalling 0·75 m^3 soil per gully metre. When applying a bulk density of 1·5 Mg m^{-3} (Method Section) the total soil loss through gully erosion was approximately 5,000 Mg soil for the sub-catchment of 33·6 ha and 148·8 Mg soil ha^{-1}. The bare patches with inter-gully erosion covered about 30% (10 ha) of the 33·6 ha sub-catchment. We estimated an inter-gully rate of erosion of 10 cm depth for the 10 ha bare patches, which resulted in a loss of 10,000 m^3 soil. The total soil loss for the entire sub-catchment over 50 years was 15,000 Mg, 446 Mg ha^{-1} or 9 Mg ha^{-1} yr^{-1}.

With a surface area of 0·8164 ha and an average soil depth of 40 cm (Table S1) for the gullies, we calculated a soil C loss through gully erosion of 53 Mg C (i.e. 65 Mg C ha^{-1} * 0·8164). The C content in the upper 10 cm soil layer was assumed to be three times higher than the mean of the entire soil horizon of 50 cm. Loss of C through inter-gully erosion was thus calculated as being 39 Mg C ha^{-1} (i.e. 65 Mg C ha^{-1} $(5*3)^{-1}$) or 390 Mg C for the 10 ha of bare patches within the sub-catchment. Total soil C loss through gully (53 Mg C) and inter-gully erosion (390 Mg C) for the sub-catchment area amounted to 443 Mg soil C (Table III).

Seventy percent of the study site was covered by vegetation. As shown in Table IV, the C stock in the vegetation was 6·16 Mg C ha^{-1} (kraalbos) or 3·63 Mg C ha^{-1} (renosterbos), respectively, resulting in a remaining aboveground C stock for the sub-catchment of 106·5 Mg C. With 30% of the sub-catchment with bare patches, 45·6 Mg aboveground plant C was lost. The total loss of aboveground (45·6 Mg C) and belowground plant C (40 Mg C, i.e. 4 Mg C ha^{-1} * 10 ha, Method Section) as well as soil C (443 Mg C) in the sub-catchment tallied to 528·6 Mg total C (Table III).

The Ecological Effects of Restoration Measures

Two years after their implementation, the check dams had positive effects on abiotic and biotic variables at the upslope side of the treatment. Most biotic variables showed 10–30 times higher values on the upslope side of the check dams as compared with the controls (Table V). Plots on the downslope side were either identical with the upslope plots or (for cover of grass and annual dicots) intermediate between upslope and control. Only cover of herbaceous perennial plants and of woody litter did not show any differences between the treatments. Soil depth increased by >100% or 10 cm at the upslope side but did not differ between downslope and control plots.

The restoration treatment of the bare patches showed fewer differences between treatment and control than the check dams (Table VI). Only total (i.e. dead plus live) vegetation cover, cover of dead grasses and dead herbaceous perennial dicots were positively affected by the treatment. We also found a strong association between geotextile and occurrence of dung (Table VII).

Cost and Benefit of Restoration

The cost per item, check dam and square metre bare-patch treatment are shown in Table VIII. The total projected cost for the treatment of the bare patches and gullies of the entire study site would amount to 1,438,328 ZAR.

With the 10 ha of bare land and a recommended stocking rate of 5 ha SSU^{-1}, the study site lost grazing for about two sheep or goat ewes. With an average reproduction rate of two lambs per ewe, sold for 1000 ZAR at the meat market, the lost income through degradation and reduced stocking density was 4000 ZAR yr^{-1}. This amount can be expected as additional income after 10 years of vegetation for recovery subsequent to the implementation of the restoration measures. At an assumed C sequestration rate of 0·5 Mg C ha^{-1} yr^{-1} the 10 ha sub-catchment that had been restored requires about 106 years to sequester the 528·6 Mg total C

Table IV. Calculation of aboveground biomass and plant C for the two dominating vegetation types at the study site

	Area covered in %	Area covered in ha	Density of plants [plant m^{-2}]	Total number of plants	Dry aboveground biomass [Mg]	Aboveground C per ha [Mg C ha^{-1}]	Total aboveground C per vegetation type [Mg]
Bare soil surface	30%	10	0	0	0	0	0
Kraalbos	25%	8·4	0·6	50·400	103·4	6·16	51·7
Renosterbos	45%	15·1	0·4	60·400	109·6	3·63	54·8
Total	100%	33·6			213·0		106·5

Species-specific formula to calculate dry aboveground biomass from allometric measurements follow Anderson *et al.* (2010). Conversion factor for dry aboveground biomass to organic carbon is 0·5 (Pettersen, 1984). For measurements and calculation, see Table S1

Table V. Indicators for restoration effects of the check dams at upslope, downslope and control plots

Variable	Control	Downslope	Upslope	f^2	p
Biotic variables					
Vegetation total (live and dead)	1·66 (0·57)[a]	10·00 (5·10)[b]	13·03 (4·67)[b]	12·540	**0·002**
Live plants	0·19 (0·12)[a]	2·54 (2·21)[b]	6·68 (4·33)[b]	13·770	**0·001**
Grass (live)	0·04 (0·02)[a]	0·39 (0·20)[a,b]	1·07 (0·39)[b]	13·340	**0·001**
Annual dicots (live)	0·00 (0·00)[a]	0·0025 (0·00)[a,b]	0·091 (0·05)[b]	3·391	**0·013**
Perennial herbaceous dicots (live)	0·15 (0·11)	2·14 (2·07)	5·53 (4·37)	0·303	0·648
Dead plants					
Total cover (dead)	1·48 (0·54)	7·46 (4·59)	6·35 (2·57)	6·480	0·038*
Grass (dead)	0·25 (0·15)[a]	5·04 (4·47)[b]	4·25 (2·45)[b]	12·380	**0·001**
Perennial herbaceous dicots (dead)	0·25 (0·25)[a]	1·70 (0·83)[b]	2·05 (0·88)[b]	5·387	**0·016**
Woody litter	0·95 (0·49)	0·72 (0·43)	0·05 (0·05)	2·131	0·113
Abiotic variables					
Penetration resistance [Mpa]	3·38 (0·29)[a]	3·26 (0·29)[a]	2·17 (0·24)[b]	9·869	**0·007**
Soil depth [cm]	8·08 (0·94)[a]	12·78 (1·84)[a]	20·31 (1·90)[b]	26·470	**<0·001**

The first values in the sample group columns are the mean values of the samples; the values in brackets are the standard errors. Values with different letters differ significantly. Significant p-values (p <0·05) are printed in bold.
*No significant result after Bonferroni Correction.

that has been lost during the post-WWII period. The C sequestration rate of 0·5 Mg C ha^{-1} yr^{-1} equals 19 Mg CO_2e yr^{-1} for the 10 ha restored sub-catchment and could yield an annual income through payment for C sequestration of between 1425 and 2925 ZAR and (after 10 years of resting) for additional livestock of 4000 ZAR. After 20 years, the NPV of the restoration was still −1,382,914 ZAR (for 1 Mg CO_2e = 150 ZAR) or −1,401,607 ZAR (for 1 Mg CO_2e = 75 ZAR). The NPV after 20 years was positive only when the price for 1 Mg CO_2e was 5977 ZAR; this represents an increase of a magnitude of 40 to 80 compared with the current price.

DISCUSSION

Ecological Effects of Degradation and Restoration Treatments

Soil erosion in semiarid South Africa has been a concern since nearly 150 years (Hoffman & Ashwell, 2001; Keay-Bright & Boardman, 2009). Yet, the actual soil erosion rates in different parts of South Africa are poorly documented (Decker *et al*., 2011). Boardman *et al*. (2015) record erosion rates for badlands in the Eastern Karoo (477 mm p yr^{-1}) with 53–145 Mg ha^{-1} yr^{-1}, which exceeds the average erosion rate reported for pastures in Asia, Africa and South America of 30–40 Mg $ha^{-1}yr^{-1}$ (Pimentel *et al*., 1995) by far. Compared with that, the erosion rate of 9 Mg ha^{-1} yr^{-1} determined for our study site seems to be moderate. A global concern regarding soil erosion is the mobilisation of the soil C pool, which is about 4·2 times the atmospheric C pool (Lal, 2001). Even warm desert and warm temperate life zones have an estimated soil C stock of 14–76 Mg C ha^{-1} (Post *et al*., 1982). The soil C stock of 65 Mg C ha^{-1} determined for our study area (Mills & Fey, 2004) is within this range and exceeded the calculated lost plant C (85·6 Mg aboveground and belowground plant C) by a magnitude of five.

Our case study showed that even low-cost restoration treatments can have a positive effect on the ecosystem and reverse the degradation effects by collection of fine material, facilitation of plant growth in the gullies, particularly upslope of the check dams, and increase vegetation cover on bare patches. The positive effects of the check dams

Table VI. Mean values (in brackets: standard errors) for biotic and abiotic variables of control and treatment (Gt + s) of bare patches

Variable	Control	Gt + s	U (df)	z	Exact p
Biotic variables					
Vegetation total (live and dead)	1·30 (0·84)	5·32 (2·06)	21·50 (9)	−2·12	**0·030**
Live plants (total)	0·80 (0·67)	1·91 (1·23)	29·00 (9)	−1·70	0·088
Grass (live)	0·00 (0·00)	0·03 (0·03)	45·00 (9)	−0·90	1·000
Annual dicots (live)	0·00 (0·00)	0·16 (0·15)	30·00 (9)	−2·11	0·087
Herbaceous perennial dicots (live)	0·80 (0·67)	1·72 (1·11)	41·00 (9)	−0·79	0·499
Dead plants total	0·31 (0·18)	3·30 (1·33)	19·00 (9)	−2·38	**0·014**
Grass (dead)	0·40 (0·03)	2·24 (0·98)	12·00 (9)	−3·03	**0·001**
Herbaceous perennial dicots (dead)	0·03 (0·03)	1·06 (0·58)	25·00 (9)	−2·17	**0·034**
Woody litter	0·23 (0·17)	0·00 (0·00)	40·00 (9)	−1·38	0·474
Litter (total)	0·19 (0·08)	0·11 (0·06)	31·00 (9)	−1·43	0·148
Abiotic variables					
Penetration resistance [MPa]	4·78 (0·09)	4·27 (0·23)	28·50 (9)	−1·64	0·098

U = Mann–Whitney U value; z = z-value; df = degree of freedom; p-values are printed in bold where sample groups differed significantly (p < 0·05).

Table VII. Contingency table for Fisher's Exact Test with number of plots in brackets and marked main diagonal for positive association of dung and geotextile

		Geotextile +	−	$\sum$ Sum
Dung	+	a (13)	b (0)	$a+b$ (13)
	−	c (17)	d (30)	$c+d$ (47)
$\sum$	Sum	$a+c$ (30)	$b+d$ (30)	$a+b+c+d=n$ (60)

can be explained by the reduction of velocity and energy of run-off water in the gully, as has also been shown by several studies on gully restoration in semiarid environments (Geyik, 1986; Conesa-Garcia & Garcia-Lorenzo, 2008; Nyssen *et al*., 2010). The reduced velocity leads to sedimentation of fine material and ponding (Nyssen *et al*., 2010; Nichols *et al*., 2012; Polyakov *et al*., 2014). Ponding water that has also been observed upslope of check dams in our study site may explain the lower penetration resistance and, together with the diaspores caught by the check dams, the increased plant growth upslope of the check dams.

A similar positive effect may be ascribed to the geotextile covering the bare soil surfaces: it slows down the run-off water of rainstorms, impairs splash impact of raindrops and subsequent water erosion (Lekha, 2004; Bhattacharyya *et al*., 2010; Smets *et al*., 2011). Slower percolation of the rainwater through the geotextile into the soil improves infiltration. In addition, geotextile has a mulching effect, which balances the soil surface temperature, reduces the evaporation and thus leads to higher moisture content in soil (Bhattacharyya *et al*., 2010). In our study, loosening of soil surfaces had been undertaken to further improve infiltration. These treatments, however, did not reduce penetration resistance, which suggests that infiltration of rain was not improved much either. This assumption is supported by the relatively poor long-term response of plants to the bare-patch treatment. The spreading of seed-rich topsoil and the rough structure of geotextile that catches diaspores increased the overall (i.e. live plus dead) cover of plants. During the dry period, when we assessed the treatment effects, the majority of the newly established annual and perennial plants on the bare patches were dead. This suggests that the improvement of the moisture content was not sufficient yet to sustain the newly established plants throughout the dry summer season. The better conditions for the re-establishment of vegetation in restored gullies supports the findings by other studies that found lack of water a potentially limiting factor in restoration of plant cover in drylands (Hanke *et al*., 2011; Vallejo *et al*., 2012). Over the subsequent years, the accumulation of plant cover on the bare patches – even if it dies back during the dry season – is likely to have a mulching effect and increase soil moisture and will eventually facilitate the establishment of perennial vegetation cover throughout the year. The positive effects of vegetation cover on soil moisture and organic matter have been shown for apricot orchards under Mediterranean climate in Spain (Keesstra *et al*., 2016).

Financial Cost and Benefit of Restoration

Ecological restoration enhances a bundle of soil-related ecosystem services, such as provision of organic carbon and macro-nutrients and water storage capacity (Lal, 2001; Gulati & Rai, 2014) and filtering for groundwater quality (Keesstra *et al*., 2012), which are captured when accounting the value of restored ecosystems (De Groot *et al*., 2013).

Table VIII. Cost items of the restoration measure, subdivided into costs per cost item, cost per check dam and square metre restored bare patch (Oettlé, unpublished data)

	Amount per unit in ZAR
(a) Costs items	
Geotextile (per bale, i.e. 1000 m^2)	5,823·23
Transport (three bales of geotextile from Cape Town, i.e. 2x 350 km)	1,313·50
Daily transport to the farm for restoration work (four persons)	131·35
Labour (per person and 8 hours working day)	120·00
(b) Costs per check dam	
Geotextile (2 m × 1·2 m)	15·22
Poles were harvested on the farm as part of another project	No cost
Transport (proportional per check dam)	4·20
Labour (8 check dams can be built per person per day)	15·00
Total cost for 1 check dam	34·42
Cost for 200 check dams installed in 2011	6884·00
Projected cost for 300 check dams needed to treat all gullies in the study site	10,326·00
(c) Bare patches	
Geotextile per m^2	6·34
Transport (from Cape Town to the farmland; per m^2)	0·44
Labour (preparation of the surface per m^2 = 0·5 h m^{-1} incl. sawdust)	7·50
Bare patches per m^2 (labour + geotextile + transport)	14·28
Projected cost for 10-ha bare patches at the study site	1,428,000·00
Projected total cost for bare patch and gully restoration at the entire study site	1,438,328·00

However, the appreciation of ecosystem services through the global economy is poor. Payment for C sequestration through the global market of CO_2 equivalents is currently perhaps the only established system in this regard. Particularly, systems that recover from degradation and C depletion have been identified as valuable C sinks (Lal, 2009). Farmers who invest in ecosystem restoration can aim to benefit from the payment for C sequestration, even in semiarid regions of South Africa (Mills *et al*., 2013). But as has been shown in our study and for even more intensively used ostrich farms in semiarid South Africa (Herling *et al*., 2009), restoration costs exceed the current benefit through payments for C sequestration and other ecosystem services (e.g. additional grazing, higher yield) if the degraded area is extensive, and productivity and recovery rate are slow. This makes restoring dryland ecosystems unaffordable for farmers without support from the public sector (Herling *et al*., 2009; Mills *et al*., 2013). Policy makers need to provide adequate incentives to encourage restoration in order to support ecosystem services. These incentives for the restoration of the degraded ecosystem could be increased or decreased depending on the economic return (in terms of ecosystem services) of the restoration measure (Galati *et al*., 2015).

CONCLUSION

Drylands support the livelihood of a large proportion of the human population worldwide, and these livelihoods are threatened through ecosystem degradation. Our study showed that the costs of restoration measures, even if based on low-cost material and local labour, may far exceed the anticipated financial return from such investments within the foreseeable future. Financial support by the public sector through accessible and sufficient payment for ecosystem services is thus an essential component of supporting farmers' efforts to restore their drylands.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site:

Figure S1. Scheme and equations to calculate the gully volume.
Figure S2. Photographs of gullies and check dams.
Table S1. Gully volume data and calculations
Table S2. Biomass calculations

