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A 13-year record of erosion on badland sites in the Karoo, South Africa

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ABSTRACT

Land degradation in South Africa has been of concern for over a hundred years with both climate change and inappropriate land management (overgrazing) being proposed as primary drivers. However, there are few quantitative studies of degradation and, in particular, few of erosion by water. Badlands, taken here to be the landform which results from extreme erosion , have been notably neglected.

We report on 13 consecutive years of erosion pin measurements of badland erosion on ten study sites in the Sneeuberg uplands of the eastern Karoo in South Africa. The study sites are on Holocene colluvium which mantles footslopes. They have been subject to overgrazing for at least 100 years, c. 1850-1950. Currently they are lightly grazed by sheep. The area receives about 500 mm rainfall per year. The sites are remote, with only informal, farmer-operated, daily raingauges nearby. The nearest sub-daily raingauge is c. 55 km distant. Also we report on an analysis of the erosion pin data which focuses on establishing the origins and context of the badlands, including the relationship between study sites and adjacent valley-bottom gully systems; compare erosion rates on our study sites with rates determined by erosion pins on other badland sites; and discuss the implications of these erosion rates for landscape development and off-site impacts.

Net erosion rates on the study sites are relatively high compared to global badland rates and range from 3.1 to 8.5 mm yr^{-1} which may be extrapolated to 53 to 145 t ha yr^{-1} (using a measured bulk density of 1.7 g cm^{-3}). However, comparisons with badland sites elsewhere are difficult because of different measuring methodologies, lithologies, climate and dominant processes.

Erosion rates on the study sites are strongly influenced by rainfall amounts and, in particular, by daily rainfall events which exceed ~10mm: this is the threshold intensity at which runoff has been observed to commence on badlands. Of significance, but of lesser influence, is weathering, mainly by wetting and drying: this prepares bare surfaces for erosion. However, questions remain regarding the role of site characteristics, and of processes at each site, in determining between-site differences in erosion rate.

Crude extrapolation of current rates of erosion, in conjunction with depths of incision into the badlands, suggests that badland development started around 200 years ago, probably as a response to the introduction of European-style stock farming which resulted in overgrazing. We assume, but cannot quantify, the additional influence of periods of drought and burning in the erosional history of the area. Intermittent connection of these badlands to valley-bottom gullies and therefore to small farm dams and ultimately to large water storage reservoirs increases their impact on local water resources.

KEY WORDS: soil erosion, badlands, erosion pins, overgrazing, Karoo, South Africa, dam sedimentation

INTRODUCTION

Soil erosion by water is widely recognised as the dominant form of land degradation globally and as a serious threat to food production and ecosystem health (Oldeman et al., 1991; Montgomery, 2007). Badlands are an extreme form of erosional landscape.

Whilst there is a clear preference for badlands to develop in semi-arid and seasonal climatic regimes (Torri and Rodolfi, 2000; Howard, 2009), they occur on many lithologies and in a diversity of climates (Table 1). Thus many definitions of badland exist. However, attributes which are common to all definitions include:

- deeply dissected landscape
- high drainage density
- lack of vegetation
- erosion into soft materials
- due to the loss of soil, a lack of value for agriculture or pasture

(Goudie, 2004; Gregory, 2010; Howard, 2010; Moore, 1952; Soil Science Society of America, 1987; Wainwright and Brazier, 2011). A general definition of badlands which brings together these attributes is one by Torri and Rodolfi (2000):

> 'densely dissected areas, which have been severely degraded and where soil has disappeared or lost most of its fertility. The combined effect of climate and badland use prevents the soil forming or recovering its fertility and erosion prevails' (p 123).

The highly eroded portions of the South African landscape which are the focus of this study are, by the above definition, badlands. They are however of a smaller spatial extent than classic badlands in the USA and the Mediterranean basin (Table 1).

South African land degradation: the context

Concern has been expressed for over a hundred years about land degradation in South Africa (Gordon, 1904; Anon, 1923; Rowntree, 2013). This concern has usually been in association with fears about the loss of good quality grazing and the impact on farm productivity. In discussions concerning the dominant cause of land degradation, overgrazing was widely perceived as the cause although such debates also suggested roles for climate change, the frequency of drought, burning and management practices. The perceived changes relate to vegetation change and increased soil erosion, mainly by water. This inconclusive dialogue has, within South Africa, been characterised as the 'desertification debate' (Acocks, 1953; Meadows, 2003a). A qualitative national survey of erosion based on expert opinion was published by Hoffman and Ashwell (2001). Compton et al. (2010) highlight substantial twentieth century increases in erosion in the Upper Orange River catchment from intensely cultivated land and grazed areas. The potential for serious erosion as a result of agricultural change is illustrated in a pioneering study where economic and political factors encouraged the conversion of slopes in the Swartland to wheat farming (Talbot, 1947; Meadows, 2003b). A review of soil erosion and land degradation in South Africa has recently been published (Boardman et al., 2012).

In South Africa, both badlands and gullies (dongas) are important manifestations of severe land degradation. Gullies have recently been the subject of studies both in the Karoo and in KwaZulu-Natal (Boardman, 2014, Rowntree, 2013; Lyons et al, 2014). In this paper we concentrate on the development of badlands, which do not necessarily include gullies. Badlands in South Africa are reported from the Eastern Cape by Boardman et al. (2003), Kakembo and Rowntree (2003), Boardman and Foster (2008), Keay-Bright and Boardman (2009) and Kakembo et al. (2009); and from KwaZulu-Natal by Watson (2000) and Clarke et al., (2003). The association of South African badlands with abandoned cultivated land has been pointed out by Kakembo and Rowntree (2003), Sonneveld et al. (2005) and Keay-Bright and Boardman (2006).

Aim

The main aim of this paper is to report on measurements of erosion and accumulation, made using erosion pins, at badland sites in the Karoo. These study sites have been measured for over 13 consecutive years. This constitutes one of the longest regularly measured data sets from badlands anywhere in the world. The programme of measurement was established, in part, in response to pleas for long-term measurements which have been made since the early days of badland research (Campbell, 1982). In South Africa, the need for 'long-term data sets and appropriate monitoring approaches' has been advocated by O'Connor and Roux (1995).

The secondary aim is to present an analysis of this erosion pin data. This primarily attempts to establish the origins and context of the badlands within the generally degraded Karoo landscape; including the relationship between badlands and their partial and intermittent connection to valley-bottom gully systems in the sediment cascade. We also compare erosion rates on our study sites with rates determined by erosion pins on badland sites in locations other than South Africa. Finally, we discuss the implications of these erosion rates for landscape development and off-site impacts in the area.

Study area and sites

The study area is in the Sneeuberg uplands which rise to 2502 m at Kompasberg mountain. The area is drained by the Klein Seekoi (Small Seacow) river, which is a north flowing headwater tributary of the Orange (Figure 1). The ten study sites are within this area, at altitudes ranging from 1698 to 1755 m (Table 2). High ground comprises Triassic Katberg Formation sandstone and mudstone with dolerite intrusions; the lower ground is underlain by Permian Balfour Formation shales and sandstones. Up to 6 m of Quaternary colluvium and alluvium overlies bedrock on footslopes and valley bottoms (Holmes et al., 2003; Boardman et al., 2005). Depth to bedrock at the erosion pin sites varies but at only three of them has incision reached bedrock (Table 2). This incision into colluvium varies between 0.50 m and 2 m. Soils on badlands often lack A and B horizons due to erosion and surfaces are compact (bulk densities 1.6 – 1.9 g cm^{-3}, see Table 2). Mean organic matter content of these badland soils is 2.44 % (CV = 18.44) (Dickie and Parsons, 2012). The Karoo badlands are developed in non-dispersive soils and piping is not a factor. The vegetation of the area is typically *Elytropappus rhinocerotis-Euryops annae* shrubland with *Merxmuellera* (now *Tenaxia*) *disticha* tussocks. Around the northern base of Kompasberg is a shrubby variant of Karoo

Escarpment Grassland (Mucina and Rutherford 2006; Dr V.R. Clark, personal communication). Vegetation cover on all erosion pin sites is <20% and on most is well under that value (Table 2). It comprises remnant shrubs on interfluves and occasional recolonising grasses in areas of temporary alluviation in rills and on footslopes (Figure 2). Shrubs and grass clumps inhibit erosion locally but their overall influence on erosion is minimal.

Major gully systems occupy all valley bottoms and many topographic depressions: they feed into the incised ephemeral Klein Seekoi river. There has been little change to the size and extent of valley-bottom gully systems since 1945 (Keay-Bright and Boardman, 2006) although they have probably influenced landscape connectivity (Foster et al., 2007).

Rainfall in the study area is strongly seasonal with most precipitation falling between January and March (Foster et al., 2007). The study sites are remote, hence there are no formal raingauges nearby. The nearest meteorological station is at Grootfontein agricultural research station near Middelburg, some 55 km to the north-east of, and 450 m lower than, our study area. Whilst the collection of daily rainfall data began here in 1878, sub-daily data has been available for only a very short period and is no longer collected (since the automatic weather station was stolen: pers comm from Justin Du Toit, 6 Oct 2014). Figure 3 shows annual rainfall at Middelburg. Analysis of annual rainfall depth at Middelburg shows no significant linear trend during the last 100 years. However, there are notable long-term changes in the magnitude of daily rainfall. The daily depth that in the period 1900-1950 had a return period of 80 years, in 1950-2000 had a return period of only six years (Foster et al., 2012). Also, the average rainday-only rainfall has increased from ~6 mm to ~12 mm over the same time period (Boardman and Foster, 2008).

Figure 3 also shows shorter annual records from three informal, farmer-operated daily raingauges. Two of these are within the study area, one is c. 23 km to the south. These records are of lower quality. Gauges may be moved or closed, and there are occasional ambiguities and possible omissions within the records. Nonetheless, we judge these informal raingauges to be generally reliable. Quantification of their trustworthiness is not straightforward however: even where these informal raingauges are in reasonably close proximity, the convectional nature of precipitation in this mountainous terrain means that rainfall is spatially very variable. For example, on 25 Nov 2014, daily rainfall at Lucernvale Farm was 7 mm. But c. 7 km away at Compassberg Farm, 20 mm fell in 20 minutes on the same day.

Given the considerable distance to the nearest formal raingauge and the spatial variability of rainfall in the study area, we have chosen to use data from these farmer-operated informal raingauges in our analysis. This naturally has implications for the interpretation of our results. The informal daily rainfall record that is used for all subsequent analysis in this paper is from a daily raingauge which was situated at Compassberg Farm and operated from 1987 until January 2010, and was then moved to Lucernvale Farm. The Compassberg Farm gauge was within 5 km of all erosion pin sites and the Lucernvale Farm gauge is within 7 km (see Figure 1). For the remainder of this paper, we will refer to this combined record as 'Compassberg Farm' rainfall. It shows that the study area is particularly wet compared to other parts of the Karoo. The annual average rainfall at Compassberg Farm for 1988-2009 was 477 mm. For comparison, annual averages for lower altitude sites with long records are 357 mm for Weltevreden Farm (1904-2010) and 335 mm for Middelburg (1878-2011).

Selection of the erosion pin sites

The ten erosion pin sites (Figures 1 and 2 and Table 2) were selected as representing a reasonable sample of the badland component of the landscape. They are not identical. This is deliberate, since they were chosen so as cover the range of surface conditions found on badland areas within the study area. All sites include small areas of remaining surfaces (interfluves) which were subsequently incised by channels. These channels are of various sizes, from rill-sized up to (on two sites) gully-sized. Site O1 is the least similar with a small retreating scarp clearly seen on Figure 2. Yet despite this diversity it is important to note that the study sites are not representative of the wider landscape in the study area, since no less-degraded sites are included. Erosion rates reported here, from these ten study sites, will therefore be considerably higher than erosion rates measured at randomly-selected locations within the wider landscape. Whilst it would have been interesting to also include measurements from less-degraded sites, there is a practical difficulty in doing so. Measurement uncertainty using erosion pins (discussed below) is not trivial: thus there would, at these less-degraded sites, be a notable danger of the erosion 'signal' being overwhelmed by measurement-uncertainty 'noise'. We do have longer term sediment yield data reconstructed from rates of dam sedimentation but these have been reported elsewhere (e.g. Foster et al. 2007; 2012) and are not directly comparable with erosion pin data as badlands generally occupy no more than 15% of the total area of any of the catchments.

The historical context of erosion on the study sites

Interaction between trekboers from the Cape Colony and indigenous Bushmen was occurring in the late 1700s with acquisition of livestock by Bushmen (Sampson, 1995). Farms were established in the Klein Seekoi valley in the early 1800s. In the Middelburg magisterial district stock numbers were high from ~1860 – ~1960, and were well above average for the Karoo, at what would now be regarded as environmentally damaging levels (Keay-Bright and Boardman, 2007). Farmers in the area also cultivated valley-bottom ‘lands’ for arable crops, chiefly dryland wheat. In the study area wheat was widespread in the 1950s and 60s, but by the 1980s it had ceased apparently due to a combination of social, economic and climatic reasons. In recent years a number of farms have switched from domesticated stock to wildlife and tourism (Chesterman, 2009).

Areas of badland within the study area are in general clearly represented as areas of erosion on the most recent 1:50,000 topographic map (Chief Directorate: Surveys and Mapping, 2001). Also, Google Earth (2002) provides high-quality imagery of the badland areas. These two sources were used, together with extensive field work, to map these badland areas (Figure 1). The badland areas are generally surrounded by what we have classed as ‘degraded areas’, which while less severely eroded than the badland areas proper, still have poor vegetation cover: grasses in particular are lacking and shrubs dominate. Keay-Bright and Boardman (2006) estimate that both 'badlands' and 'degraded areas' covered ~17.8% of the study area in 1945. This falls to ~14.5% in 2002 probably relating to falling stock numbers. Areas classed as 'badlands' represent ~4% of the area covered by Figure 1. Vegetation on the badlands appears relatively stable: changes were not recorded from one visit to another.

In this area, badlands which occur on footslopes appear to be the result of overgrazing and damage to vegetation between the late nineteenth century and the 1950s (Keay-Bright and Boardman 2006, 2007). Badlands in valley-bottom locations are the result of the abandonment and subsequent degradation of formerly cultivated land: abandonment took place between ~1920 and ~1980. However, overgrazing also subsequently affected abandoned cultivated land. Air photographs show that all ten study sites are in areas that have not been cultivated. It is therefore assumed that degradation on these sites was initiated principally by overgrazing.

An important element of the cultural landscape of the study area is the existence of large numbers of small farm dams built largely in the Twentieth Century for water provision for stock, and in some cases to control valley-bottom gully erosion (Boardman and Foster, 2011). Sedimentation in the dams allows environmental histories to be reconstructed (e.g. Foster et al., 2007; 2008; Boardman et al., 2010; Rowntree and Foster, 2012; Foster et al., 2012).

Finally, while the emphasis in this paper is on the impact of runoff on the badland surfaces, local farmers also report occasional episodes of wind erosion on ploughed soils; it is therefore likely that this process may contribute to the loss of fine particles in dry periods from the badlands. However, rates remain un-quantified.

METHODOLOGY

Details of the ten erosion pin sites are given in Table 2, with photographs of each in Figure 2. All have very little vegetation: however, in most other respects the study sites are quite diverse.

At each site, an array of 25 metal erosion pins, each 335 mm long x 3 mm diameter, was set up. Pins were inserted carefully to minimise disturbance to the soil. Each pin array covers an area of either 16 m^2 (1 x 1 m grid: four sites) or 32 m^2 (2 x 1 m grid: six sites). The pins were spray painted to aid relocation and to prevent rust. Four sites were established in March 2001 and the remainder in December 2001. Pin exposure was measured with a steel tape up to 17 times between 2001 and February 2012 (Table 3). Measurements were taken approximately annually, supplemented by a few extra measurements at shorter intervals, sometimes of just a few days (this occurred mostly during the earlier part of the study). Most measurements were taken between December and March i.e. during the southern hemisphere summer.

In addition to changes in pin exposure, the presence or absence of vegetation around each pin, and a 'topographic category' for each pin, was noted. These data are only briefly considered in this paper (see 'Within-site results') but will be used in further research.

Since the sites are remote, they are not subject to human interference. However sheep trampling (even with much reduced stock numbers compared with historical densities) occasionally disturbed pins and led to some data loss; damaged pins (denoted 'missing' in Table 3) were replaced at each measurement date. Other pin losses were associated with channel-side collapse.

Increased pin exposure was observed on the majority of pins: this was assumed to indicate erosion. Decreased pin exposure was observed on a minority of pins, and was assumed to indicate accumulation. A small minority of pins showed no change in exposure between measurement periods.

A separate experiment was carried out to quantify pin measurement error. The same person carried out ten re-measurements of each of the 25 pins at one site: these re-measurements were done in a random sequence. Deviations from the mean were approximately normally distributed, with a standard deviation of about 1.5 mm. We interpret this as an estimate of RMS error, i.e. the uncertainty which results from unavoidable and unpredictable random measurement error. Other erosion pin studies have been more optimistic regarding measurement uncertainty. Sirvent et al. (1997) report the accuracy of erosion pin measurements as being +/-0.5 mm, and Benito et al.

(1992) report ‘potential measurement errors’ of 1 mm; however neither give details of how these values were obtained.

RESULTS

Change in the exposure of a single pin between two measurement dates may be very small, just a few mm. Since RMS uncertainty is around 1.5 mm, it is clear there can be little confidence in any analysis of the measurement data which involves short time intervals and/or relatively few pins i.e. when summed or individual changes of pin exposure are little bigger than the RMS error. In such a case, there is a strong likelihood of the erosion or accumulation 'signal' being drowned in the 'noise' of measurement uncertainty. Conversely, we can be more confident regarding results derived from analysis which involves large totals of change in exposure depth, derived from summed measurements over many years and/or from many pins. Thus our analysis was carried out in two stages, starting with the largest samples (all sites during the whole period of measurement) and moving to smaller samples (various subsets).

Results from all sites

This first stage of analysis brings together data from all ten study sites during the whole period of measurement for each site. Doing this of course ignores between-site differences, instead considering each site to be an independent sample of the most degraded parts of the landscape.

For each site, the average rate of erosion over the whole period of measurement was calculated by summing the total depth eroded (i.e. the total from all pin measurements showing increased exposure) then dividing by the time of measurement and the total number of pins at the site (25 in every case). The average rate of accumulation was calculated in a similar manner, with average net erosion being the difference between the two. For the all-site long-term averages, it was necessary to weight each site's contribution by the length of time it had been in operation. Table 3 shows long-term average rates of erosion, accumulation and net erosion both for individual sites and for all sites. The uncertainty intervals for erosion and accumulation in Table 3 are one standard deviation: note that in every case, except for net erosion on site C2, these uncertainty intervals are smaller than the RMS uncertainty. Thus we can be reasonably confident regarding these rates.

Figure 4a shows individual erosion measurements for all sites plotted against rainfall at Compassberg Farm during the measurement interval, together with best-fit line from a linear regression. Whilst there is considerable scatter, the fit of the regression line is significant at 99%, in part due to the relatively large (n=173) number of data points. Figure 4b is similar, but with erosion plotted against the number of daily rainfall events > 10 mm during each measurement interval. Again the fit is significant at 99% despite considerable scatter. Note that data from all measurement intervals, even those of very short duration, were used in these regressions.

Regression of accumulation against rainfall amounts, and against the number of daily rainfalls > 10 mm, indicated little or no relationship. Similar regressions of net erosion gave results which are roughly intermediate between erosion and accumulation.

Results for individual sites

Whilst all ten sites are situated in highly-degraded badland areas, the diversity of site characteristics (Table 2 and Figure 2) suggest that each site will respond differently to a given rainfall event. The considerable scatter in both graphs of Figure 4 supports this. Thus the next stage of analysis focuses on results for individual sites. Less scatter (and possibly more geomorphological insight) might be expected by adopting this per-site focus: however the downside is that the smaller numbers of measurements involved, considered alongside the not-insignificant RMS uncertainty in pin measurement, inevitably leads to a decrease in confidence in these per-site results.

Table 3 shows the average rate of erosion and accumulation for each site over the whole period of measurement. Average rates of erosion on the ten study sites during the whole period of measurement range between 5.9 and 13.1 mm yr^{-1}; average rates of accumulation range between 1.3 and 5.1 mm yr^{-1}; average rates of net erosion range between 2.5 and 8.5 mm yr^{-1}. The highest rate of erosion and the second-highest rate of accumulation occur at a single site (C2), but otherwise there is only a weak relationship between the average rate of erosion and the average rate of accumulation for each site: the relatively steep site UL, for example, has the second-highest erosion rate but the second-lowest accumulation rate.

A temporal view of erosion, accumulation, and net erosion on each site is shown in Figure 5. While the temporal response of every site is broadly similar, there are some clear differences between sites. A relatively high value for erosion during 2004 appears at all sites, but this peak is much less prominent at two of them (LUO and UUO). There is a notable high value for erosion in 2010 at UL and LL, however the erosion value for 2010 is relatively low at the other sites, while at C1 this 2010 peak is absent. There is little inter-site consistency in temporal rates of accumulation. For each site, the temporal pattern of erosion and the temporal pattern of accumulation are only weakly linked.

Figure 6 shows the relationship at each site between the average depth of erosion on all eroding pins for each measurement interval, and Compassberg Farm rainfall during that measurement interval.

Figure 7 is similar, but shows the relationship between the average depth of erosion and the number of daily rainfall events > 10 mm during each measurement interval. A best-fit linear regression line is also shown for each site. Erosion amounts are clearly related to rainfall. In both Figure 6 and Figure 7 the fit was significant at 99% confidence for six sites; significant at 95% for two sites; and not significant at two sites. At a majority of sites, scatter is lower than for the all-sites relationships shown in Figure 4. The highest correlation coefficient is still only 0.6, however. There is some tendency for the sites with higher average erosion rates to also have higher correlation coefficients. Again, note that data from all measurement intervals, even those of very short duration, were used in these regressions. Thus some points in Figures 4, 6 and 7 refer to erosion and rainfall during only one or two days, others refer to erosion and rainfall during a whole year.

The regressions were repeated (graphs not shown) using temporally amalgamated data, so that each point referred to time intervals of more nearly equal duration. However doing this did not consistently improve regression results. A number of other possible correlations were also evaluated. Erosion, accumulation, and net erosion for each site were each regressed against:

- Rainfall amount during each measurement period
- Rainfall amount during each measurement period multiplied by the length (in days) of the dry spell preceding each rainfall event (a form of antecedent precipitation index)
- The number of rainfall events > 10 mm during each measurement period
- Rainfall amount derived only from events > 10 mm during each measurement period.

None of these produced better results, in terms of scatter and significance, than the per-site results shown in Figures 6 and 7.

As with the all-sites analysis, regression of each site's accumulation against rainfall amounts, and against the number of daily rainfalls > 10 mm, showed very weak or no relationships, with similar regressions of net erosion giving results which are roughly intermediate between erosion and accumulation.

Within-site results

Since the erosion pins were set up in a spatial grid, and results are available for each pin during the whole period of measurement, there is clearly some scope for a within-site, spatially-oriented stage of analysis. Tempting as this may be from the perspective of geomorphological insight, it is also potentially dangerous since the potential for spurious pattern-finding is high. Each point on a site's spatial grid is a single erosion pin. Even on a map showing long-term totals of erosion, accumulation or net erosion for the grid, values at each point result from only a rather small number of pin measurements. Given the RMS uncertainty associated with pin measurements, the 'signal' at each pin is in even greater danger of being overwhelmed by uncertainty-derived 'noise'. If maps are made showing spatial patterns of erosion, accumulation or net erosion at each measurement date, then distinguishing 'signal' from 'noise' becomes problematic in the extreme.

Nonetheless, we have produced maps showing long-term patterns of erosion, accumulation and net erosion for each site: these are available online as supplementary material. Movies showing the temporal change in spatial patterns of erosion, accumulation and net erosion are also available online: these should be considered tentative in the extreme.

These site maps also show vegetation and 'topographic category' around each pin. Plans are in place for Digital Elevation Models to be produced for some of the sites. These DEMs will be used, in conjunction with the above mentioned maps, in a subsequent study.

DISCUSSION

Process

Despite carrying out a variety of exploratory analyses, our substantive finding is a rather predictable one: on most of the ten study sites there is a reasonably strong relationship between rainfall and erosion. Erosion rates on a majority of the ten sites are sufficiently similar to be considered to be drawn from the same statistical population: thus in statistical terms, these sites are replicates. Nevertheless, there are clearly some inter-site differences. But inter-site variation in erosion, accumulation and net erosion does not follow any clear pattern (with one exception: see below). Also none of the site characteristics shown in Table 2 are effective in explaining inter-site variation in erosion, accumulation and net erosion.

Runoff on the badland areas is generated by rainfall amounts as low as 10 mm which has been observed over time periods of as little as 1 hour. Many of the surfaces are compacted with bulk densities of ~1.6 – 1.9 g cm^{-3}; such events result in a shallow depth of wetting and rill and interrill flow within minutes of the commencement of rainfall (cf. Bryan and Yair, 1982). The most clearly compacted site, C1 (Figure 2), has relatively low erosion rates. Variations in compaction are likely to contribute to variations in erosion between pin sites.

Rainfall, and the resulting runoff, is the main driver of erosion; this is indicated by positive correlations between rain amounts, numbers of events > 10mm and erosion (Figures 6 and 7). Similarly, Clarke and Rendell (2006, Figure 10) show a positive relationship between erosion and cumulative rainfall. Rainsplash plays an important role in dislodging surface particles: splashed particles are often found coating erosion pins. Patterns of flow routing on the study sites are not, in most cases, obvious. Within-site flow routing is likely to be temporally variable (Favis-Mortlock et al., 2000) which may contribute to the scatter of the correlations shown in Figures 6 and 7. A clear seasonal pattern to erosion is also implied, with an emphasis on the wetter summer months December – March. This is unsurprising in a strongly seasonal climate. Scoging (1982) in southern Spain explains strong seasonal erosion as a function of intense summer storms whereas Benito et al. (1992) in the Ebro basin suggests a pattern of summer weathering and evacuation of debris in winter by runoff. Weathering also dislodges material which is subsequently removed by runoff. Wetting and drying are likely to be the main drivers of weathering on these sites. There is little evidence of effective frost action. The lack of perfect correlation between rainfall and erosion suggests that the erosion is likely influenced by the amount of weathering. Erosional effectiveness is therefore detachment-limited (cf. Howard 2009 p. 273). Weathering of mudstone and sandstone clasts on an alluvial fan at Compassberg indicates the potential for rapid breakdown of particles on exposed badland surfaces (Boardman, 2015). While some particles are redistributed within the plot, others may be lost by wind erosion which is reported in the area.

Not all accumulation within the pin sites is weathered material that has not yet been removed by runoff. Some within-site accumulation appears to result from deposition at locations where runoff locally decreases in transport competence, i.e. where erosion is transport-limited. It may be, then, that these sites are both detachment-limited and transport-limited, but at different times and at different within-site locations.

Comparison with other badland studies

The badlands described here differ from more developed badland areas in other areas in several respects. They are developed in colluvium and incision is rarely more than 2 m deep. This suggests relatively recent initiation and also reflects the limited depth of colluvium. The review by Howard (2009) suggests that most badlands are developed in weathered bedrock and the incision of some is in excess of 100 m. Mass movements, except for occasional small-scale channel-side collapse, are not observed. Frost appears to be ineffective due to the dryness of winters. Neotectonics are also not an issue in the Sneeuberg. In many respects, the comparable areas are in western New South Wales

(Fanning 1994, 1999) rather than the Mediterranean, or North America, although rainfall amounts are very different (Table 1).

Haigh (1977) in a review of erosion pin studies lists six which were at badland sites, all in north America. Erosion pin studies listed in Saunders and Young (1985) are not on badlands. An extensive database of erosion rates on Mediterranean badlands using several measurement procedures is presented by Nadal-Romero et al. (2011). Twelve of these used erosion pin measurements. Clarke and Rendell (2006) review the great range of rates and variability on badlands due to differences in lithology, rainfall and measurement procedures.

We focus on erosion rates assessed by erosion pin measurements and Table 1 presents a selection of rates from badlands using these techniques. Detailed analysis of variation in rates from area to area is not productive although some useful conclusions can be drawn:

1. Lithology and climate vary considerably. The low erosion rates at some sites appear to be a function of low rainfall e.g south east Spain (Scoging, 1982)
2. Variation within areas is considerable e.g. Alexander's (1982) sites in southern Italy
3. The short time period of most studies: it is not therefore possible to analyse in a meaningful way variations in time
4. It is not always clear how average rates of erosion have been calculated and whether accumulation has been included e.g Alexander's (1982) 20-30 mm yr^{-1}
5. There is significant variation in process from badland to badland e.g. creep is a major process on the Mancos Shale badland (Godfrey et al., 2008) and biological soil crusts influence erosion at the Tabernas badlands (Lazaro et al., 2008). Neither of these processes is observed at the Karoo sites.
6. The scale of measurement frequently varies cf. Campbell's (1982) 1 m^2 plots and the great range of scales listed in the Nadal-Romero et al. (2011) database. This leads to a difficulty of comparing between different measurement methods particularly rates provided by erosion pins and sediment losses from plots. Studies have come to different conclusions regarding comparative rates from pins and collector devices (reviewed by Sirvent et al., 1997). We note the advantage of using pins in that net erosion rates take into account both erosion and deposition; in other studies this has usually been implicit in the average values but we have made it explicit in Table 3.

However, despite limitations, the data in Table 3 illustrate the generally high rates of erosion characteristic of badlands. A median rate of ~10 mm yr^{-1} (100 m^3 $ha^{-1}yr^{-1}$) is high even for areas disturbed by human activities. Saunders and Young (1983) note the huge range of accelerated erosion rates produced by various human interventions in the natural landscape.

Finally, it is useful to consider the results of this study in the wider South African context. Esler et al. (2010 p. 60) suggest rates of erosion of only 1 - 4 t ha^{-1} yr^{-1} for areas of the South African Karoo with less than 20% vegetation cover. This is a substantial contrast with rates reported here. However, these areas may be much drier than our study area; scale of measurement may also explain these contrasts.

Validation of results

Partial validation of pin-based erosion estimates from our study sites can be achieved from two sources. Firstly, soil samples from flat interfluves within the GH1 study site show no detectable ^{137}Cs. Nearby undisturbed reference sites show ^{137}Cs to a depth of ~230 mm (Foster et al., 2005). This suggests that a minimum of 230 mm of erosion has occurred in the last ~56 years (i.e. since 1958, the beginning of significant ^{137}Cs fallout from weapons testing) on interfluve areas of the GH1 study site. Those erosion pins on the GH1 site which are located on between-channel interfluves, and which are unprotected by vegetation, show an average net erosion rate of 5.9 mm yr^{-1}. This extrapolates to ~329 mm of erosion during the last 56 years, which exceeds the minimum value derived from the ^{137}CS measurements. Caesium-137 is, however, found in protected soil pedestals beneath living bushes on the GH1 study site interfluves: the extrapolated depth of net erosion for vegetation-protected interfluve pins during the last 56 years on the GH1 site is only 63 mm.

Secondly, sediment sampling during small storms from the valley-bottom gully draining the Good Hope badlands gives an estimated export rate of 55 t ha^{-1} yr^{-1} (Keay-Bright and Boardman, 2009). Table 3 shows that net erosion from the GH1 study site is ~3.3 mm yr^{-1}. Assuming a bulk density of 1.7 g cm^{-3}, this is ~56 t ha^{-1} yr^{-1} giving a sediment delivery ratio close to unity. For the GH2 study site, net erosion (Table 3) is 4.3 mm yr^{-1}, which represents ~73 t ha^{-1} yr^{-1} and indicating a sediment delivery ratio of ~0.75. Both sediment delivery ratios are plausible since GH1 is closer to the valley-bottom gully than is GH2.

From these two partial validations, one based on ^{137}Cs and one based on measurement of exported sediment, we believe that our measurements of net erosion rates at the GH study sites are reasonable estimates. By extension, we also consider that measurements of net erosion rates at our other study sites are equally reasonable.

Age and origin of badlands

It is clear that some badlands in or near our study area have been initiated, or their development enhanced, by the incision of adjacent valley-bottom gullies; this is the case, for example, at all four Oppermanskraal sites cf. Wells and Gutierrez (1982) and Nogueras et al. (2000). But it is also likely that the development of badlands led to greater incision of valley-bottom gullies due to the increase in runoff. Rainfall simulation experiments (Boardman et al., 2003) in this area show 10x more runoff from bare areas compared to vegetated areas; bare, badland areas at six of the ten erosion pin sites feed directly into gullies. However, the building of small dams across valley-bottom gullies has led to alluviation in the gullies. Causes of gully incision are varied. Boardman (2014) suggests that in the Sneeuberg the initiation of valley-bottom gullies was a result of the establishment of European style farming, overgrazing and the use of the area as a route for settlers and miners. There is evidence for development of gullies from early 19th century wagon tracks and associated outspanning of oxen along trekking routes (Neville et al., 1994; Rowntree, 2013). The issue, as in other areas, is how the well vegetated valley bottoms were degraded to the extent that incision occurred (Cooke and Reeves, 1976), or shear stress of flowing water was sufficient to overcome protective vegetation cover (Boardman 2014). The origin of the gullies and the badlands are probably closely related.

A crude estimate of the date of initiation of erosion in our study area can be made by backcasting current net erosion rates. Doing so involves two major assumptions: an initial level surface at each site, and consistency of erosion rates through time. The second is the most dubious, since the A and B horizons of the original uncompacted soils would have eroded more quickly than do the compacted former subsoils which are all that remain at each site. Also rates of incision would have slowed greatly once bedrock was encountered in the within-site channels (cf. Table 2). Rainfall is also assumed roughly constant: this assumption is less problematic since there is limited evidence of any notable changes in rainfall. However there were periods of drought (especially in the 1920s and 30s) which may have damaged the vegetation. Burning of vegetation would also have had an effect, as would stock numbers, which were much higher in the period 1850-1950 than at present.

Nonetheless, this crude procedure suggests a plausible order-of-magnitude date for the initiation of the badlands: ~200 years ago. The average rate of net erosion for all sites is about 5.4 mm yr^{-1} (maximum 8.7 and minimum 3.2). So in 200 years, depth lost would be 1.1 m (maximum 1.7, minimum 0.6 m). Age estimates for each site are given in Table 4; these should be treated with even greater caution.

Limitations and implications

Rainfall data used for the remote badland sites of this study were, of necessity, derived from informal farmer-operated raingauges. However, as previously discussed, we judge these data to be generally reliable.

The more serious criticism of using pins on badlands is that the rates apply to relatively small areas which are not representative of the catchment as a whole. We acknowledge this point. Great contrasts clearly exist between badland and well-vegetated areas with many intermediate situations. Rainfall simulation experiments show that runoff from badland areas is 10x that from better vegetated areas and that erosion is 6x more effective (Boardman et al. 2003). High rates of erosion from badlands representing small areas of catchments are highlighted by Fanning (1994) and Clarke and Rendall (2010). They also emphasise the issue of badlands often being decoupled from ephemeral drainage networks.

The lack of connectivity of the majority of badland sites in the study area to valley-bottom gully systems is reflected in sediment yields to small dams which are in the range 4-8 t ha^{-1} yr^{-1} (Boardman et al., 2010; Foster et al., 2012). Four erosion pin sites feed sediment directly into gullies that lead to Dam 37 (see Figure 1 for location). This major farm dam has effectively infilled, since ~1950s when it was built, with an estimated 200,000 m^3 of sediment. The catchment includes a large area of degraded land as well as the six badland monitoring sites shown on Figure 1. These sites would have contributed ^{137}Cs-rich sediment until they were stripped of their topsoil. The impact of badlands on sedimentation in farm reservoirs can be illustrated at the nearby Ganora dam by use of magnetic susceptibility measures and examination of sediment cores from the dam. Badlands within the catchment became connected to a gully system that fed into the dam in the 1960s, which led to a fourfold increase in sediment yield up to ~ 1600 t km^{-2} yr^{-1} (Foster et al., 2012).

Rates of erosion reported here for badland sites are at least two orders of magnitude higher than generally accepted rates of soil formation (cf. Montgomery, 2007 p. 24). Soil formation is absent except on small areas of shrub survival or grass encroachment – usually where sediment accumulation has taken place in the base of within-site channels. Low levels of grazing still occur although stocking densities are much reduced compared to the period 1860 – 1960.

Although the high rates of erosion on badland areas are, at the present time, probably contributing small amounts of sediment to the valley-bottom gullies, there is significant risk in the future of enhanced connectivity between badlands and gullies and therefore small farm dams. Many dams are already full of sediment and a proportion have suffered breaching and release of sediment thus potentially increasing rates of sediment deposition in downstream water supply reservoirs (Boardman and Foster, 2011). This risk is increased by the current trend for a greater number of high magnitude rainfall events. Since there is a positive relationship between erosion and the number of events > 10 mm (Figure 7b), a rise in the number of such events will necessarily lead to an increase in erosion, all else being equal.

FUTURE WORK

These are complex and challenging sites, with data collection made more difficult by the sites' remoteness. The analysis described here shows broad patterns, but questions regarding between-site differences remain unanswered. A limitation of the present analysis, too, is that it considers only values of erosion and accumulation over the whole areas of each site, or on that fraction of each site's area which is, in any measurement period, showing erosion or accumulation. Clearly, there is further information which can be gained by looking at the within-site spatial patterns of erosion and accumulation. There will inevitably be a signal-to-noise aspect when considering within-site variations: however the longer the record, the stronger the signal. A start has already been made on this within-site data (see supplementary material) for selected sites, with future work aiming to link within-site patterns of erosion and accumulation both with DEM-derived topography, and the other attributes which were also noted when each pin measurement was made. Finally, erosion pin field measurements are ongoing.

CONCLUSION

Ten small badland areas in the Karoo area of South Africa have been monitored for 13 years using arrays of 25 erosion pins at each site. Measurements were made on up to 20 occasions during this time period. The study areas are remote, and rainfall is spatially quite variable. However, local farmer-operated informal raingauges that are read daily allow us to investigate the relationship between rainfall, runoff and erosion. On bare, compacted badland areas runoff occurs with as little as 10 mm of rainfall. Erosion is correlated with both amounts of rainfall and numbers of events >10 mm in each measurement period. However, it is clear that prior weathering of the badland surfaces also plays a part in determining amounts of erosion. The erosion pin methodology allows us to estimate net erosion taking into account both pins showing erosion and those showing deposition.

Net amounts range from 3.1 to 8.5 mm yr^{-1} which may be extrapolated to 53 to 145 t ha yr^{-1} (using a measured bulk density of 1.7 g cm^{-3}). The badlands appear to be the result of overgrazing since European style farming principally of sheep, was introduced into the area in the nineteenth century. The degree of connectivity of the badlands to valley-bottom gully systems, and thereby to farm dams, is variable but likely to increase. A continuing trend of intensification of rainfall and breaching of small dams poses a threat of increased sedimentation in downvalley water supply reservoirs with a proportion of these sediments originating from badlands.

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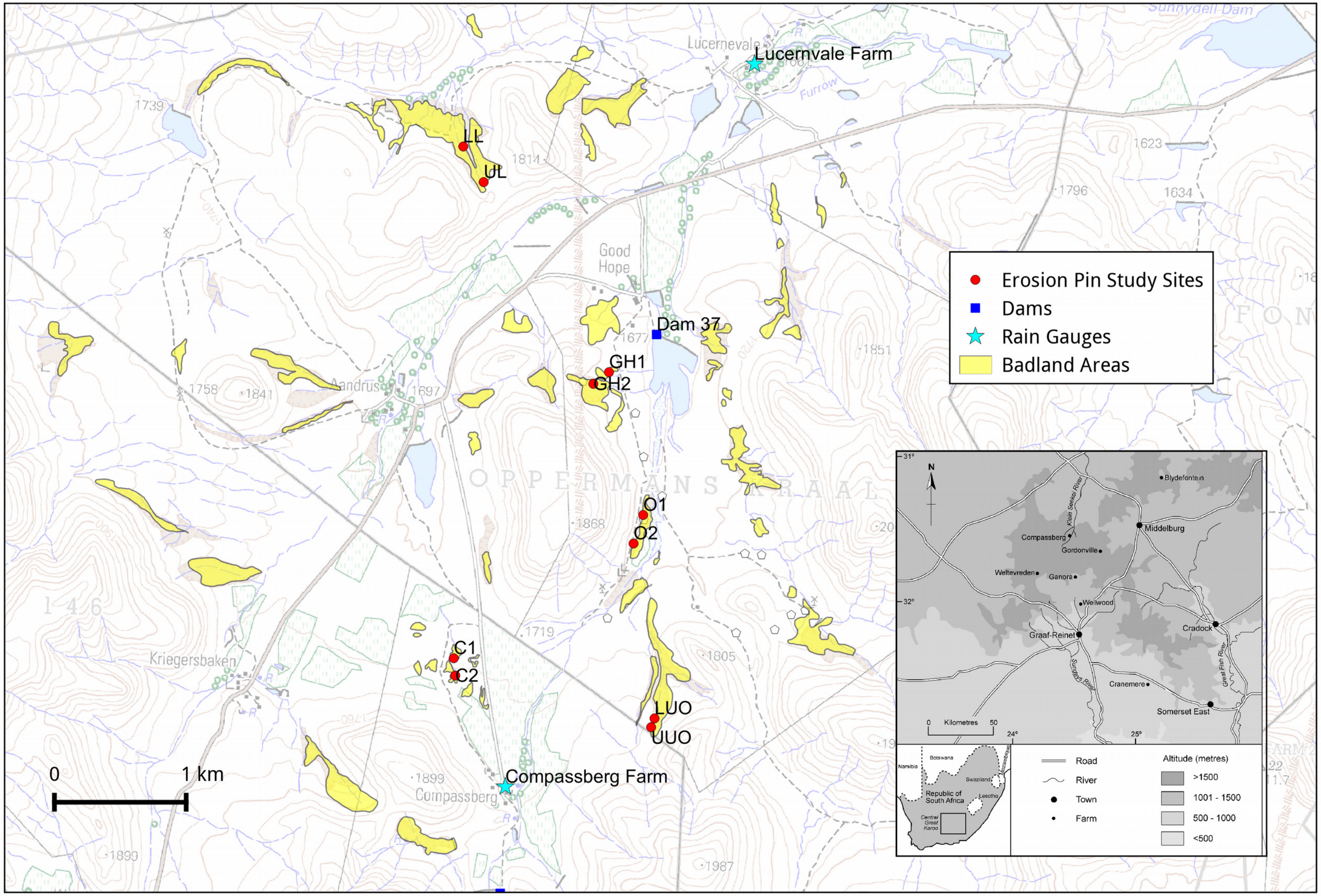


Figure 1. Location of the study area, erosion pin sites and badlands. See text regarding the two raingauge sites


GH1


GH2


C1


C2


O1


O2


LUO


UUO


LL


UL

Figure 2. Photographs of the ten erosion pin study sites. Larger versions are available online at ***

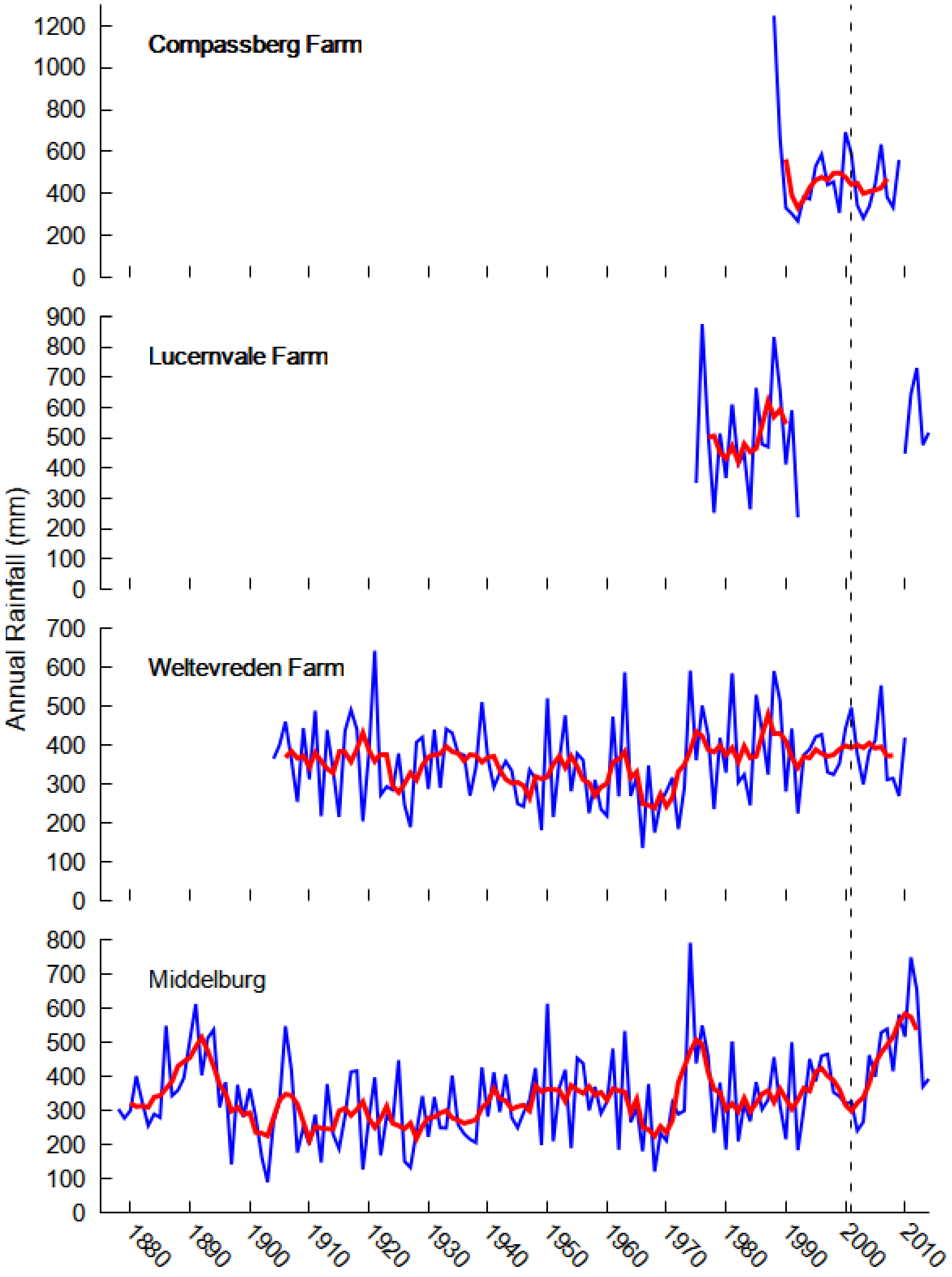


Figure 3. Time series of annual rain at Compassberg Farm, Lucernvale Farm, Weltevreden Farm and Middelburg. Note the different y-axis scale for each graph. For each graph, the solid line is annual rain, the dashed line is a 5-year moving average. The vertical line indicates the start of monitoring on the 10 erosion pin sites

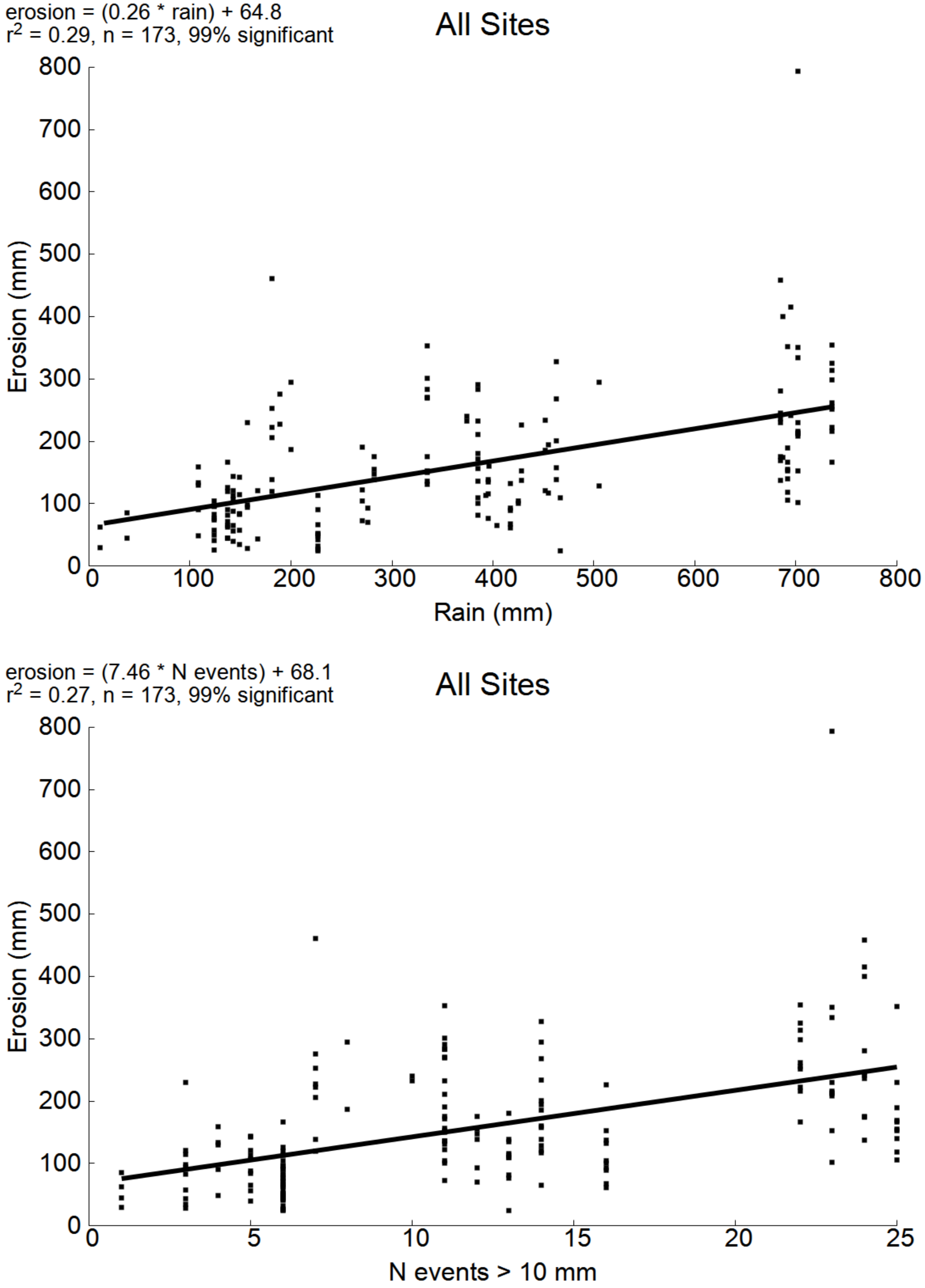
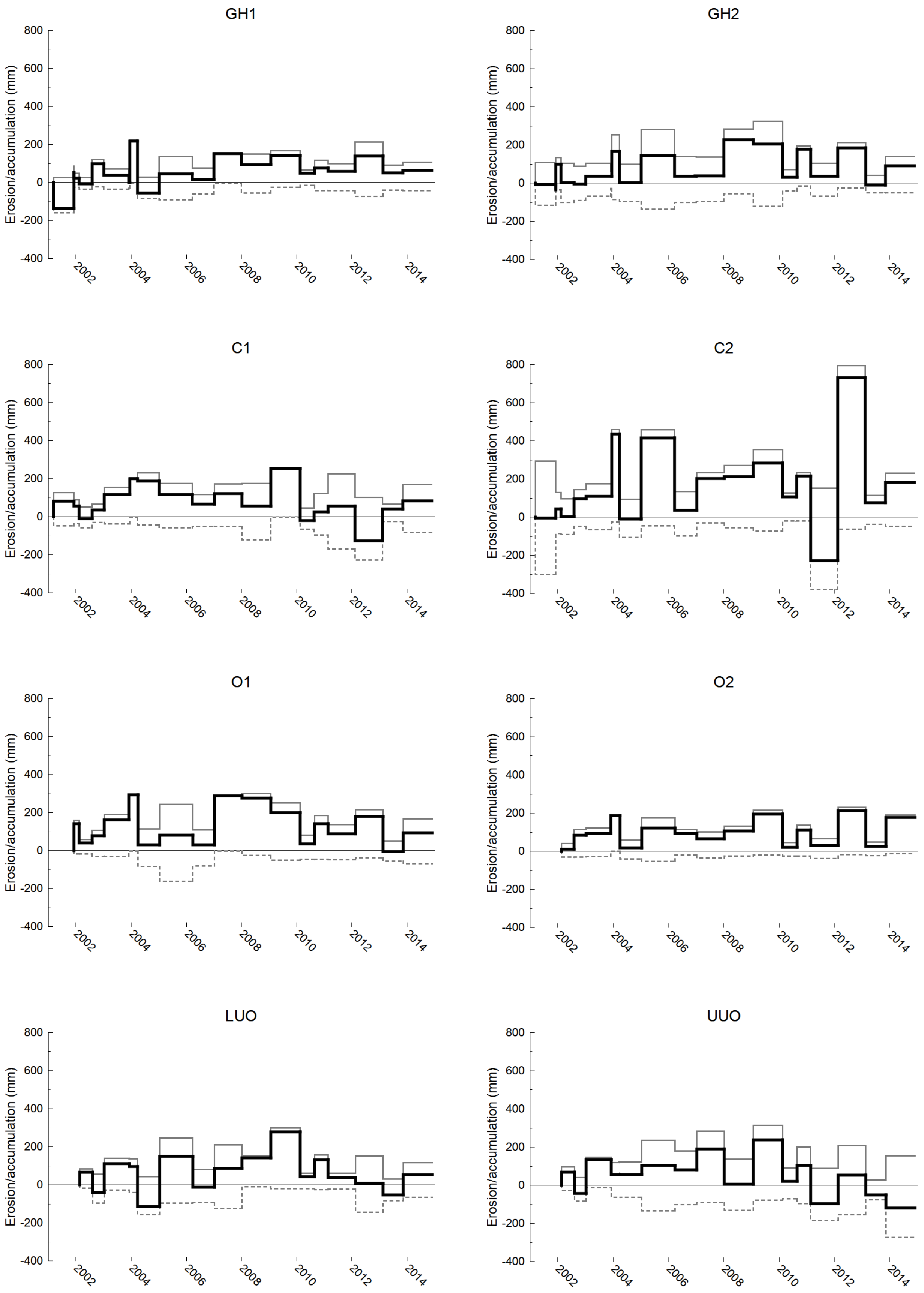


Figure 4. The upper graph shows erosion (mm) v. total rainfall (mm) during each measurement interval for all sites. The lower graph shows erosion (mm) v. the number of daily rainfall events > 10 mm during each measurement interval for all sites


GH1
GH2
C1
C2
O1
O2
LUO
UUO
Erosion/accumulation (mm)
800
600
400
200
0
-200
-400
2002
2004
2006
2008
2010
2012
2014

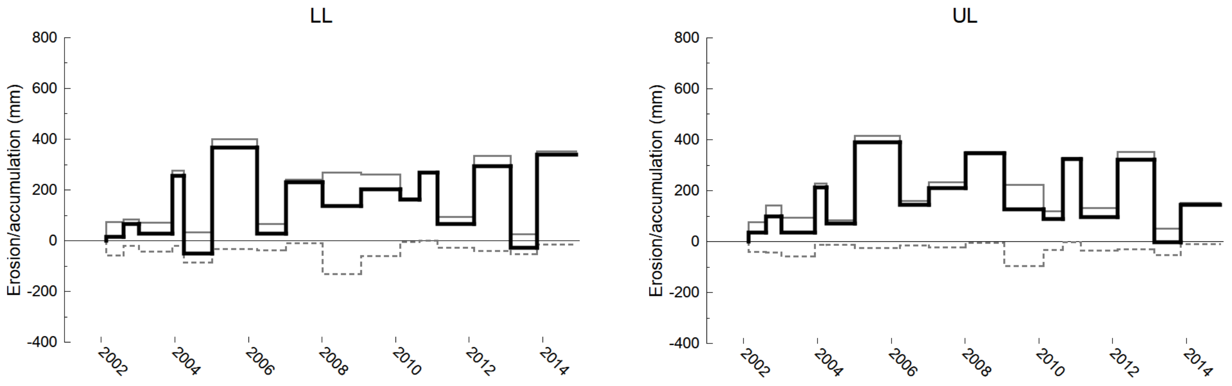
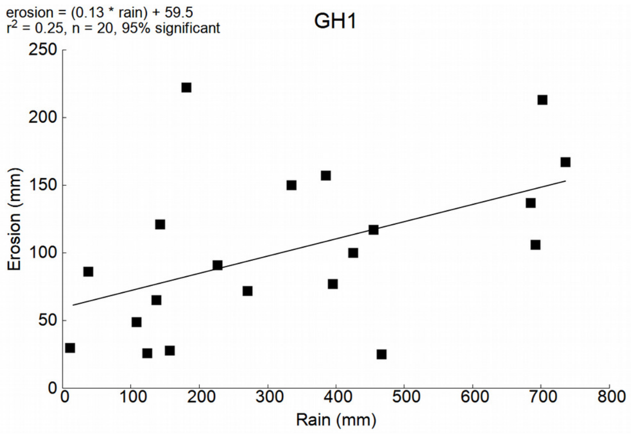
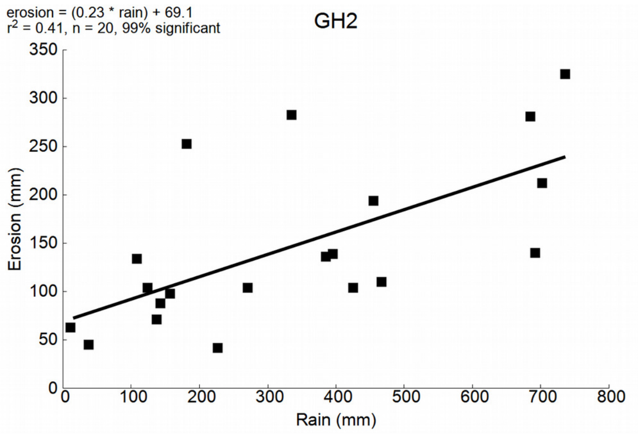
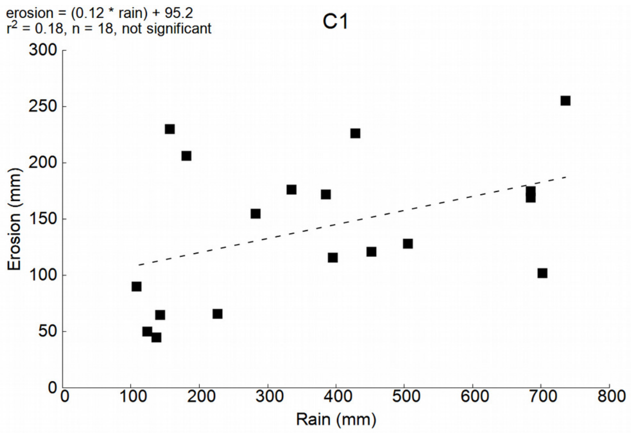
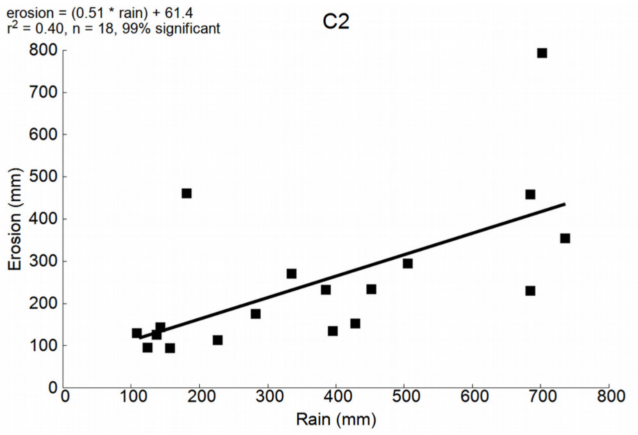


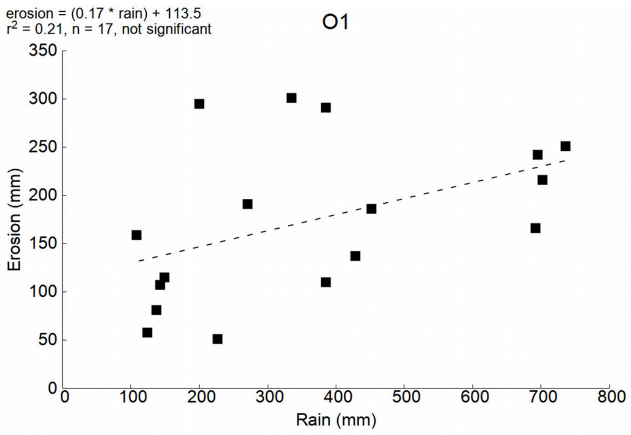
Figure 5. Time series of erosion, accumulation, and net erosion (mm) during each measurement interval for each erosion pin site. Erosion is positive, and is shown by a solid grey line; accumulation is negative, and is shown by a dashed grey line; net erosion is shown by a thick black line

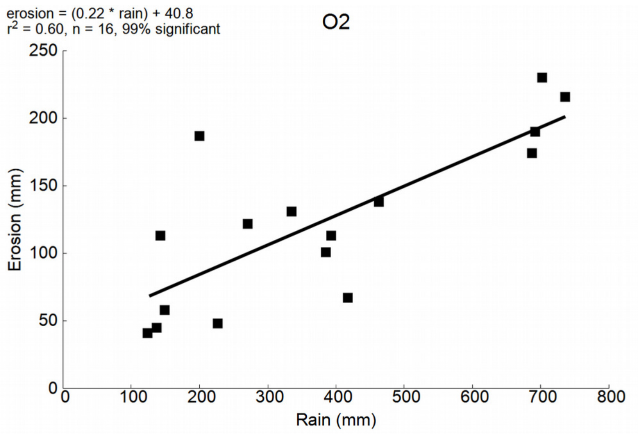

erosion = (0.13 * rain) + 59.5
r² = 0.25, n = 20, 95% significant
GH1
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
0
100
200
300
400
500
600
700
800

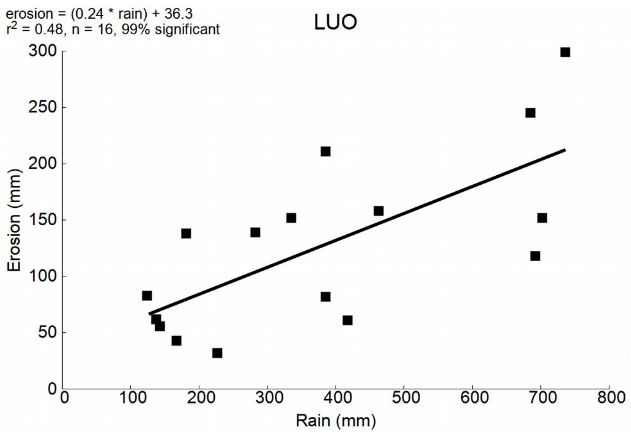

erosion = (0.23 * rain) + 69.1
r² = 0.41, n = 20, 99% significant
GH2
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
300
350
0
100
200
300
400
500
600
700
800

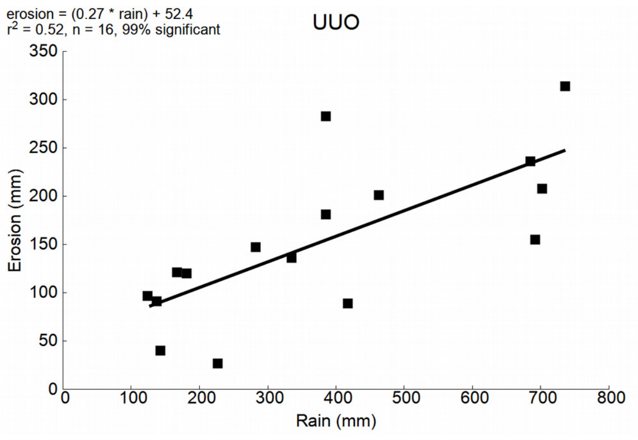

erosion = (0.12 * rain) + 95.2
r² = 0.18, n = 18, not significant
C1
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700
800


erosion = (0.51 * rain) + 61.4
r² = 0.40, n = 18, 99% significant
C2
Erosion (mm)
Rain (mm)
0
100
200
300
400
500
600
700
800
0
100
200
300
400
500
600
700
800


erosion = (0.17 * rain) + 113.5
r² = 0.21, n = 17, not significant
O1
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
300
350
0
100
200
300
400
500
600
700
800


erosion = (0.22 * rain) + 40.8
r² = 0.60, n = 16, 99% significant
O2
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
0
100
200
300
400
500
600
700
800


erosion = (0.24 * rain) + 36.3
r² = 0.48, n = 16, 99% significant
LUO
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700
800


erosion = (0.27 * rain) + 52.4
r² = 0.52, n = 16, 99% significant
UUO
Erosion (mm)
Rain (mm)
0
50
100
150
200
250
300
350
0
100
200
300
400
500
600
700
800

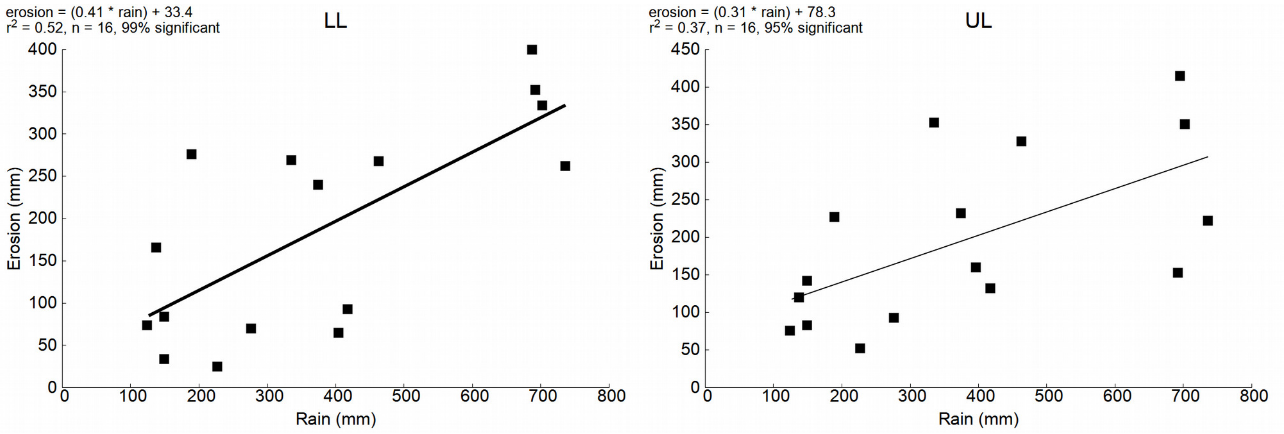
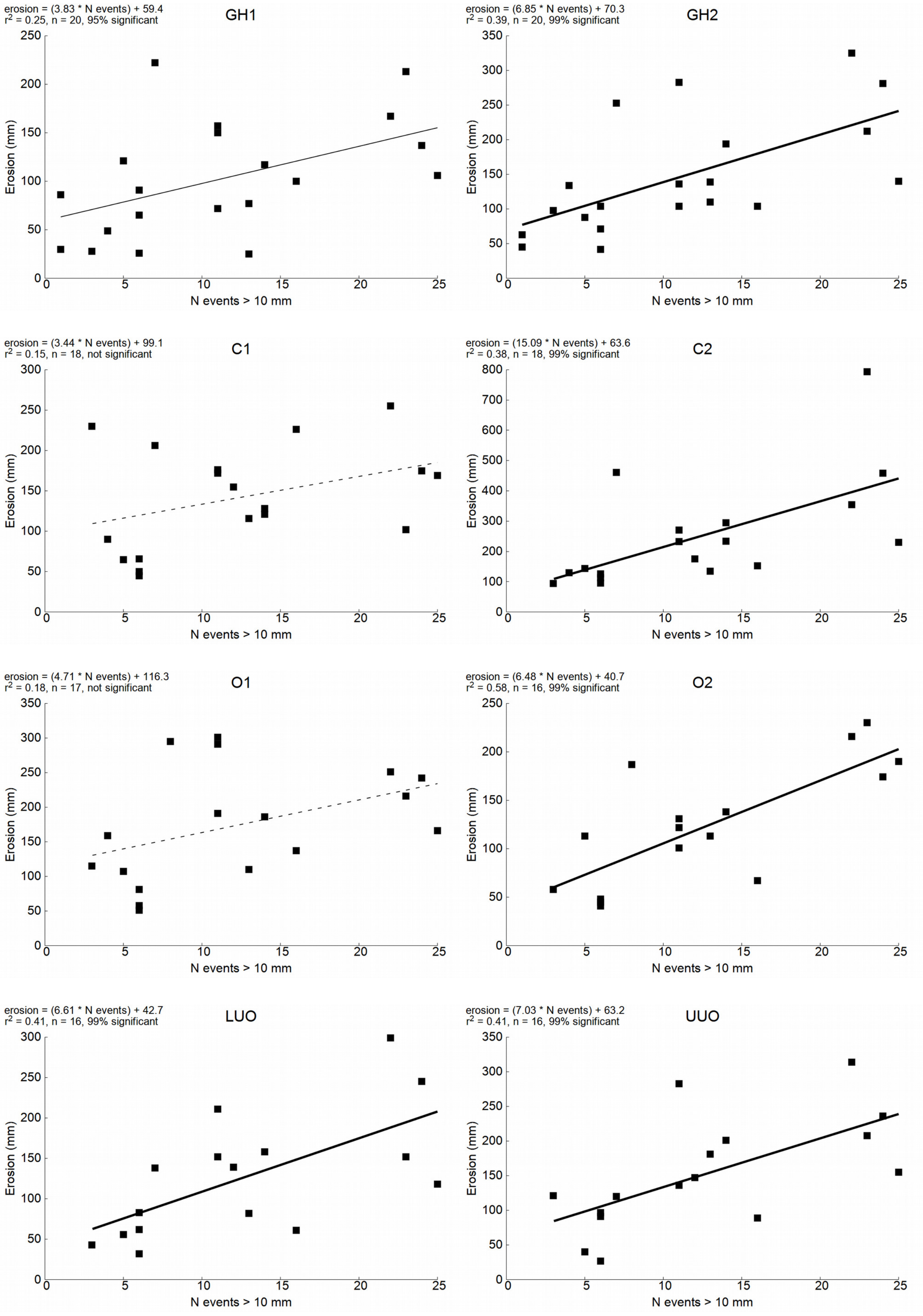


Figure 6. Average erosion (mm) on all eroding pins v. total rainfall (mm) during each measurement interval for each site. Note the different y axis scales. Relationships which are not significant at 95% are shown with a dashed line, relationships which are significant at 95% are shown with a solid line, and a thicker regression line indicates a relationship which is significant at 99%


erosion = (3.83 * N events) + 59.4
r2 = 0.25, n = 20, 95% significant
GH1
Erosion (mm)
0
50
100
150
200
250
N events > 10 mm
0
5
10
15
20
25
erosion = (6.85 * N events) + 70.3
r2 = 0.39, n = 20, 99% significant
GH2
Erosion (mm)
0
50
100
150
200
250
300
350
N events > 10 mm
erosion = (3.44 * N events) + 99.1
r2 = 0.15, n = 18, not significant
C1
Erosion (mm)
0
50
100
150
200
250
300
N events > 10 mm
erosion = (15.09 * N events) + 63.6
r2 = 0.38, n = 18, 99% significant
C2
Erosion (mm)
0
100
200
300
400
500
600
700
800
N events > 10 mm
erosion = (4.71 * N events) + 116.3
r2 = 0.18, n = 17, not significant
O1
Erosion (mm)
0
50
100
150
200
250
300
350
N events > 10 mm
erosion = (6.48 * N events) + 40.7
r2 = 0.58, n = 16, 99% significant
O2
Erosion (mm)
0
50
100
150
200
250
N events > 10 mm
erosion = (6.61 * N events) + 42.7
r2 = 0.41, n = 16, 99% significant
LUO
Erosion (mm)
0
50
100
150
200
250
300
N events > 10 mm
erosion = (7.03 * N events) + 63.2
r2 = 0.41, n = 16, 99% significant
UUO
Erosion (mm)
0
50
100
150
200
250
300
350
N events > 10 mm

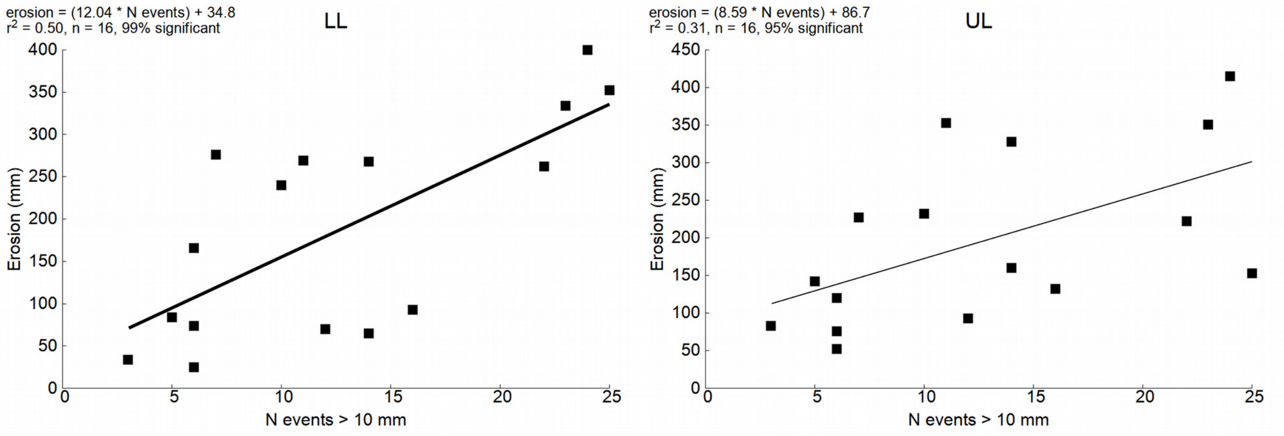


Figure 7. Average erosion (mm) on all eroding pins v. the number of daily rainfall events > 10 mm during each measurement interval for each site. Note the different y axis scales. Relationships which are not significant at 95% are shown with a dashed line, relationships which are significant at 95% are shown with a solid line, and a thicker regression line indicates a relationship which is significant at 99%

CAPTIONS TO FIGURES

Figure 1. Location of the study area, erosion pin sites and badlands. See text regarding the two raingauge sites

Figure 2. Photographs of the ten erosion pin study sites. Larger versions are available online at ***

Figure 3. Time series of annual rain at Compassberg Farm, Lucernvale Farm, Weltevreden Farm and Middelburg. Note the different y-axis scale for each graph. For each graph, the solid line is annual rain, the dashed line is a 5-year moving average. The vertical line indicates the start of monitoring on the 10 erosion pin sites

Figure 4. The upper graph shows erosion (mm) v. total rainfall (mm) during each measurement interval for all sites. The lower graph shows erosion (mm) v. the number of daily rainfall events > 10 mm during each measurement interval for all sites

Figure 5. Time series of erosion, accumulation, and net erosion (mm) during each measurement interval for each erosion pin site. Erosion is positive, and is shown by a solid grey line; accumulation is negative, and is shown by a dashed grey line; net erosion is shown by a thick black line

Figure 6. Average erosion (mm) on all eroding pins v. total rainfall (mm) during each measurement interval for each site. Note the different y axis scales. Relationships which are not significant at 95% are shown with a dashed line, relationships which are significant at 95% are shown with a solid line, and a thicker regression line indicates a relationship which is significant at 99%

Figure 7. Average erosion (mm) on all eroding pins v. the number of daily rainfall events > 10 mm during each measurement interval for each site. Note the different y axis scales. Relationships which are not significant at 95% are shown with a dashed line, relationships which are significant at 95% are shown with a solid line, and a thicker regression line indicates a relationship which is significant at 99%

TABLES

Table 1. Rates of erosion from erosion pin monitoring on badland areas. Negative values denote accumulation

Table 2. Characteristics of the ten study sites on badlands in the Compassberg area, Karoo (modified from Keay-Bright and Boardman, 2009). Slope refers to the slope of the ground surface into which the badlands are incised. The particle size analysis was based on 5 separate samples from each of the 10 badland sites using a Malvern laser granulometer with Hydro-2000 dispersal unit. Only the fraction < 2 mm was considered. Values are reported as mean values (± 1SD). (Particle size boundaries use the Wentworth scale i.e. clay : silt 2 µm; silt : sand 63 µm)

Table 3. Measurement details for the ten sites, and average rates of erosion, accumulation, and net erosion for each site and for all sites combined. Uncertainty intervals for erosion and accumulation are one standard deviation

Table 4. Estimated age of each badland study site, derived by extrapolating present-day rates of net erosion

Table 1. Rates of erosion from erosion pin monitoring on badland areas. Negative values denote accumulation

Location	**Reference**	**Average annual rainfall (mm)**	**Measurement period (years)**	**Min. erosion rate (mm/yr)**	**Max. erosion rate (mm/yr)**
SE Spain	Scoging, 1982	n/a	1	2	6
Colorado Plateau, USA	Wells & Gutierrez, 1982	220	1	3	20
Ebro basin, Spain	Benito et al., 1992	650	1.25	6	17
Ebro basin, Spain	Sirvent et al.,1997	320	2	11	22
S Italy	Alexander, 1982	600-800	2	20	30
South Dakota, USA	Schumm, 1956	c. 376	2.125	9	18
S Italy	Clarke & Rendall, 2006	625	6	7	19
New South Wales, Australia	Fanning, 1994	195	10	2	12
Tabernas, SE Spain	Lazaro et al., 2008	c. 230	11	-1.0	1.4
Caineville, Mancos Shale badland, Utah, USA	Godfrey et al., 2008	140	20	0	8.4
Gilbert badlands, Mancos Shale badland, Utah, USA	Godfrey et al., 2008	140	40	1.2	3.2

Site name	Site code	GPS co-ordinates (º)	Relief (m)	Slope (º)	Aspect (º)	Elevation (m)	Description	Bedrock in within-site channels?	Soil description	Particle size analysis (see caption)			Hydrological connectivity (Low/ Medium/ High)	
										% clay	% silt	% sand	With upslope area	With major down slope gully
Good Hope 1	GH1	S 31.682167 E 24.570472	0.6	4	100	1698	Site is across small channel and interfluve; channel very stony (sandstone) with shale bedrock at shallow depth. Little vegetation, a few shrubs on slopes. Broad interfluves, gentle slopes; many stones in channel.	Yes	Colluvium appears very thin (60–80 cm) on side slopes and shale outcrop in channels	7 (1.4)	67 (11.0)	26 (12.4)	Low	Low
Good Hope 2	GH2	S 31.683017 E 24.569200	1.8	4	110	1702	Flat sloping interfluves with shrubs with exposed roots; steep channel sidewalls; a little grass in channel. No sign of bedrock, but may be 10 cm below channel. No stones in channel. Undissected interfluve upslope of site 30 × 60 m. Rill head working into it with a pattern of shallow channels.	No	Clayey, shale-derived colluvium; few stones on surface (<2 cm).	7 (1.1)	68 (2.0)	24 (2.6)	High	Low
Compassberg 1	C1	S 31.703472 E 24.564667	0.9	2	030	1728	Signs of shallow flow on interfluve. Little vegetation and very compact. Retreat by collapse of channel heads. No recolonization on interfluves. Some recolonization in channels and on footslopes. Channel heads sometimes form arches—then collapse. Very few stones in colluvium and on surface. Distance from hillside footslope 200 m+ (gentle slope). Bedrock at shallow depth.	Yes	Colluvium 60 cm on shale outcrops in channels, thinning to 10 cm at north end of site	8 (0.8)	69 (2.7)	23 (1.9)	Low	Low
Compassberg 2	C2	S 31.703267 E 24.558967	1.5	2	000	1732	Many signs of collapse and channel down-cutting to shale. In badlands top 10 cm of soil eroded and with it most of the vegetation. Occasional patches of remnant vegetation/ shrubs.	Yes	Colluvium generally 1.2 m thick over shale. Relatively stoneless colluvium.	7 (1.2)	65 (5.1)	28 (6.3)	High	Med
Oppermanskraal 1	O1	S 31.691686 E 24.573358	0.8	9	080	1703	Site covers two interfluves and two channels. Nearby purple shale stripped of colluvial cover: large sandstone blocks and shrubs resting	No	Stony, B-horizon	5 (0.3)	59 (2.2)	36 (2.3)	High	High

							on top. Erosion pin area not yet stripped and no shale exposed. Stones have accumulated in the channels. Asymmetrical landscape at the site: gentle slopes are stone covered. Steep slopes face north, but this is not consistent pattern in area. Site feeds directly into major valley-bottom gully: quite steeply facing to east; channels of badland go right up to valley side fence. Water is fed into channel heads of badland (1–2 m deep) from shrub and boulder covered slope—not from bare ground.							
Oppermanskraal 2	O2	S 31.693833 E 24.572789	1.0	6	120	1710	On badland directly linked to major valley-bottom gully. Water is fed into channel heads of badland (1–2 m deep) from shrub and boulder covered slope—not from bare ground. No bedrock at site. Little vegetation and bare interfluves. A few shrubs in channel. Some steep channel walls. Site just below old road and wall.	No	Very stony site. Colluvium 1–2 m thick	7 (1.3)	62 (3.5)	36 (2.3)	High	High
Low Upper Oppermanskraal	LUO	S 31.705750 E 24.575028	1.2	4	020	1750	Approx. 150 m from skyline fence at very top of badlands above Oppermanskraal ruins. 1.5 m of colluvium on site itself. Site is at edge of badland area. *Pteronia tricephala* plants on interfluves and grass and shrubs in channels. Some revegetation on slopes. Bedrock shale. Depth varies in area. Dolerite on slope above.	No	Deeper colluvium than Up Upper Oppermanskraal	6 (0.7)	66 (6.3)	28 (7.0)	Low	High
Up Upper Oppermanskraal	UUO	S 31.706361 E 24.574778	0.7	4	040	1755	Relief 70 cm. Site is 25 m from skyline fence at very top of badlands above Oppermanskraal ruins. Lots of fine stones in colluvium (up to 5 cm). No bedrock on site. Deep valley-bottom gully near site. 3 m colluvium on shale. Vegetation of site mainly *Pteronia tricephala* and a few grasses. 40% bare stony ground.	No	Stony, near watershed	7 (0.7)	68 (5.4)	25 (6.1)	Low	High
Low Lucernvale	LL	S 31.667056 E 24.558222	0.8	2.5	000	1713	NW and downslope from Up Lucernvale site, 15 m from fence	No	Deeper colluvium than Up Lucernvale	6 (0.9)	72 (9.7)	22 (10.5)	Low	High

							marked with four stones. No bedrock visible. Small stones on interfluves (diameter <1 cm). Upslope fairly well vegetated with shrubs and grass on interfluve. Site mainly *Pteronia tricephala* : vegetation cover <10%. Grey colluvium overlain on interfluve by reddish colluvium.							
Upper Lucernvale	UL	S 31.669444 E 24.559944	1.5	10	000	1735	Upper edge of badlands. Above site 100 m slope to ridge. Colluvium 1.5 m thick on shale. Large sandstone blocks in valley-bottom gullies off site. Colluvium stony (3 cm diameter). Vegetation *Pteronia tricephala* on interfluves. 20% vegetation cover on site. Stony surface (<2 cm in diameter).	No	B-horizon, near watershed	7 (1.2)	63 (8.6)	30 (9.8)	Low	High

Table 2. Characteristics of the ten study sites on badlands in the Compassberg area, Karoo (modified from Keay-Bright and Boardman, 2009). Slope refers to the slope of the ground surface into which the badlands are incised. The particle size analysis was based on 5 separate samples from each of the 10 badland sites using a Malvern laser granulometer with Hydro-2000 dispersal unit. Only the fraction < 2 mm was considered. Values are reported as mean values (± 1SD). (Particle size boundaries use the Wentworth scale i.e. clay : silt 2 μm; silt : sand 63 μm)

Site code	Measurement period (years)	N measurement intervals	Erosion pin measurements					Average erosion/accumulation rate (mm yr^{-1})		
			N total	% missing	% showing erosion	% showing accumulation	% no change	Eroding pins	Accumulating pins	Net
GH1	13.72	20	500	3	53	33	11	5.9 ±0.4	2.7 ±0.2	3.3 ±0.6
GH2	13.72	20	500	5	56	33	6	8.5 ±0.5	4.3 ±0.4	4.3 ±1.0
C1	13.70	18	450	9	57	27	7	7.4 ±0.5	3.5 ±0.3	3.9 ±0.8
C2	13.70	18	450	12	58	25	5	13.1 ±1.4	4.6 ±0.6	8.5 ±2.0
O1	12.97	17	425	8	60	23	9	9.1 ±0.6	2.5 ±0.4	6.7 ±1.0
O2	12.78	16	400	9	61	20	10	6.2 ±0.3	1.3 ±0.1	4.9 ±0.4
LUO	12.79	16	400	5	56	29	10	6.4 ±0.4	3.3 ±0.5	3.1 ±0.9
UUO	12.79	16	400	1	60	33	6	7.7 ±0.5	5.1 ±0.6	2.5 ±1.1
LL	12.78	16	400	4	69	20	7	9.4 ±0.4	2.0 ±0.4	7.5 ±0.9
UL	12.78	16	400	5	71	19	5	9.8 ±0.5	1.5 ±0.2	8.3 ±0.7
Average (weighted by measurement period)								8.4 ±0.6	3.1 ±0.4	5.3 ±0.9

Table 3. Measurement details for the ten sites, and average rates of erosion, accumulation, and net erosion for each site and for all sites combined. Uncertainty intervals for erosion and accumulation are one standard deviation

Site	**Average net loss mm/yr**	**Site relief (m)**	**Estimated age (beginning of incision)**
GH1	3.3	0.6	183
GH2	4.3	1.8	452
C1	4.9	0.9	230
C2	8.5	1.5	177
O1	6.7	0.8	120
O2	4.9	1.0	206
LUO	3.1	1.2	388
UUO	2.5	0.7	277
LL	7.5	0.8	108
UL	8.3	1.5	181

Table 4. Estimated age of each badland study site, derived by extrapolating present-day rates of net erosion

Supplementary material is available online at:

http://www.soilerosion.net/karoo/