ISSN 2047-0371

3.5.3 The use of erosion pins in geomorphology

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ABSTRACT: Erosion pins have been widely used in geomorphology since the 1950s to estimate rates of change (erosion and – less commonly – accumulation) in land surfaces. They may be used for short- and long-term surveys and are quick and easy to install and measure. Erosion pins are particularly suited to bare, undisturbed environments such as badlands and sand dunes. Our recommendations for their use follow those of Haigh (1977) and Lawler (1993) but we also discuss the need for researchers to be aware of issues which arise from of measurement error, particularly for short-term studies and analytical methods which rely on few pin measurements. There is also a not inconsiderable challenge involved in extrapolating results derived from erosion pin measurements to larger areas.

KEYWORDS: badlands, erosion pins, erosion rates, measurement errors

Introduction

The basic idea behind the use of erosion pins to quantify land-surface change is very straightforward. A rod is firmly fixed into the ground (or other substrate), and a note made of the length of rod which remains exposed. After some time, this exposed length is again measured. Increased exposure is assumed to indicate erosion, and decreased exposure is assumed to indicate accumulation. Results from pin measurements may then be correlated with other measurements. These might be measurements of some hypothesized driver of land-surface change, such as rainfall.

Thus, erosion pins are a simple, robust, and relatively cheap approach to small-scale measurement of erosion rates, and one in which the design can be easily adapted to the aim of the project. The advantages of erosion pins are still more notable when compared with the expense and field/laboratory effort required by techniques such as ^{137}Cs and ^{210}Pb tracers, installation of flumes and sediment traps, laser scanning, etc. Perhaps most attractive of all, continuous monitoring of erosion pins is not necessary: useful data can be collected with occasional visits.

However, this simplicity is deceptive. Considerations of pin siting, measurement error, and interpretation of results rapidly introduce additional complexity. Thus, any geomorphological study that uses erosion pins – initially driven, perhaps, by the seductive apparent simplicity of the technique – will have to grapple with issues which may well not have been obvious at the outset, leading to possible difficulties and confusion when answering the question “What do these results tell us?”, and even (at worst) disillusionment regarding the usefulness of the technique.

But in this case forewarned is, to a large extent, forearmed. In this review of the use of erosion pins, which is an up-dating of those by Haigh (1977) and Lawler (1993), we aim to cover these complicating factors, and present some mitigating suggestions.

Historical background to the technique

As Haigh (1977) points out, the use of erosion pins originated in studies of badlands in the USA by Colbert (1956) and Schumm (1956).

The design of erosion pins has varied little. The earliest used wood (Schumm, 1956; Ranwell, 1964) but it quickly became clear that metal, and preferably non-rusting metal (either non-ferrous, or treated so as to prevent rusting) is to be preferred (Emmett, 1964; Clayton and Tinker, 1971). Brass or steel welding rods have been commonly used (Evans, 1967) but even plastic knitting needles have proved successful (Lawler, 1993). A loose-fitting washer has been used as an indicator of exposure in some studies (Kirkby and Kirkby, 1974) but not in others (Keay-Bright and Boardman, 2009; Boardman et al., 2015). The pros and cons of using washers are discussed by Haigh (1977).

A major use of erosion pins has been in badland environments (Figure 1). Nadal-Romero et al. (2011, Figure 6) compare the techniques used to measure sediment yield from Mediterranean badland areas. Erosion pins are the second most-used approach, behind only gauging stations, with 25 study sites out of 105 using pins.

Figure 1: Erosion pin site Karoo, South Africa

Many more recent papers refer to the advantages and disadvantages of using erosion pins, one such example is that by Hancock and Lowry (2015).

Spatial and temporal issues in erosion pin placement and measurement

Before driving in a single pin, placement in the wider landscape context must be very carefully considered (Lawler 1993 p. 798). Does the study aim to quantify rates of ground-surface change over the whole landscape? If so, then some form of random or stratified-random siting of pin grids may be necessary. Or does the study aim to capture rates on a particular land usage or soil type? Such perennial geomorphological considerations regarding choice of study area location are beyond the scope of this review but they are fundamental to any erosion pin study that aims to extrapolate results outside the confines of the pin grid, either spatially or temporally (see below).

An additional important consideration in the selection of pin sites in proximity to locations at which other kinds of environmental data are gathered, principally precipitation and temperature. Ideally, pin sites should be near a weather station but in many cases this is not feasible. In remote areas where medium- or long-term weather records are rare this may be a problem, and some alternative must be found. Boardman et al. (2015) use informal daily precipitation records from nearby farms, arguing that these data are generally reliable and have been gathered within 5 km of all 10 erosion pin sites but nonetheless, micro-climate differences between sites are inevitable.

Having decided on the locations where pin measurements will be made, the next step is to decide on the placement of individual pins. The aim in the placement of a single erosion pin is that the resultant measurements will adequately represent erosion, and possibly deposition, on an area around the pin. There is no general agreement on the size or indeed the limits of this area: however, assumptions regarding this area affect attempts (either overt or implicit) to estimate average rates of erosion or deposition on larger areas surrounding the pin (see below).

Neither is there general agreement on the number of replicate erosion pins that should be used, or on the spatial configuration of multiple pins. Almost all researchers have used multiple pins. Most researchers have tended to cluster pins fairly closely but the numbers have varied. For example, Higuchi et al. (2013) place 10 pins to represent a badland area: compare this with 301 pins in Evans' (1977) study and 250 pins in Boardman et al. (2015). Pins have generally been laid out in regular grids or in lines (usually straight). In both cases, a factor is ease of relocation for measurement after a considerable time period. If using erosion pins in a grid, a spacing of 1 m is frequently used e.g. Sirvent et al. (1997).

The length of time during which erosion pin measurements are conducted and the time interval between pin measurements also require serious consideration. A major factor here is the aims of the study.

If the aim is to obtain information regarding long-term average rates of erosion, then measurements should be collected over several years in order to adequately capture the effects of year-on-year variations in weather including relatively uncommon extreme events. However, most erosion pin experiments have been of rather short duration, c. 2-3 years. Longer-term studies are rare: cf those of Clarke and Rendell (2006) for 6 years, Hancock and Lowry (2015) for 9 years, Lazaro et al. (2008) for 11 years, Boardman et al. (2015) for 13 years, and Godfrey's studies of creep and surface lowering on Mancos Shale badlands for 40 years (Godfrey 1997; Godfrey et al., 2008).

If, however, the aim is to determine seasonal variations in erosion and deposition then short-duration pin experiments with a frequent measurement interval are suitable, e.g. Evans (1977): a 2-year experiment with a 4-weekly sampling interval. In all cases, sampling intervals must take into account rates of erosion and therefore measurement error (see below).

Issues with particular environments

Examples of the variety of environments where erosion pins have been used are shown in Table 1. Erosion pins are particularly suited to measurement of change on **bare peat surfaces** where erosion rates are high, e.g. because of trampling by animals and related disturbance of vegetation. However, in such a situation, trampling introduces the problem of damage to, and loss of, pins. Birnie (1993) records 50% damage to pins due to trampling. Of course, if as in this case, sheep are a major erosional factor, excluding them from the pin sites is not reasonable. Birnie (1993) suggests additional measurement techniques to check on results from pins. This study involved use of a measuring framework placed on fixed points - an approach similar to the micro-erosion meter (High and Hanna, 1970). In less heavily impacted environments losses may be lower (cf Boardman et al., 2015: <10% loss of pins). In the latter study, lost pins were always replaced and therefore only one set of measurements was missing. Other researchers have used estimated values for lost pins e.g. Lawler (1993 p. 807). Still other studies have accepted that trampling is an erosional factor (Fanning, 1994).

Table 1: The varied uses of erosion pins

Environment	Reference
Salt marsh	Ranwell (1964)
Waste tips	Haigh (1977); Schumm (1956)
River banks	Lawler 1978, 1991, 1992, 1993
Peat moorlands	Birnie (1993); Tallis (1981 p. 76)
Footpaths/trails/tracks	Streeter (1975); Summer (1986)
Badlands	Clarke and Rendell (2006); Nadal-Romero et al. (2011); Hancock and Lowry (2015); Boardman et al. (2015)
Sand dunes	Jungerius et al. (1981); Jungerius and van der Meulen (1989); Wiggs et al. (1995); Livingstone (2003)
Bare, contaminated soils	Bridges and Harding (1971)
Bare soils	Slaymaker (1972)
Gullies	Harvey (1974)

Erosion pins have been used to measure changes in the surface of **dunes** in the Netherlands and desert dunes, e.g. in Namibia. Jungerius et al. (1981) recorded changes at weekly intervals over a 2-year period. In a later study, Jungerius and van der Meulen (1989) took measurements every six months for 4 years. They compared their results from the erosion pins with air photographs showing changes in dune morphology. However, because of rapidly changing conditions, measurement of dune surfaces poses specific problems. Livingstone (2003) reports on a 21-year dune surface survey (Figure 2). Pins in place since the early 1980s provide fixed points 'so that each survey can be related to the others'. In rapidly changing conditions pins were measured once every 7 to 10 days to the nearest 5 mm (Wiggs et al., 1995). Further developments of these long-term dune studies using pins are reported in Eckardt et al. (2013) and Besler et al. (2013).

Figure 2: Steel posts on sand dune, Namibia (photo Ian Livingstone).

Many approaches have been used to assess river channel changes and **river bank retreat** including erosion pins. Lawler (1993) provides a very full review that lists 39 papers where erosion pins have been used to measure river bank retreat. In order to confront the challenge of not knowing when small increments of change took place Lawler developed a system of automatic recording of change using an adapted erosion pin, the Photo-Electronic Erosion Pin (PEEP) system. Retreat of the river bank exposes photovoltaic cells in the pin to light which increases the voltage output. Changes are recorded on a data logger and can be directly related to changes in river stage (Lawler 1991, 1992).

Erosion pins have been widely used on **badlands** particularly in the Mediterranean basin (Nadal-Romero et al., 2011). They are ideal for use in these areas that exhibit high erosion rates, bare or relatively bare surfaces, and minimum disruption by human activities. However, many such studies are for relatively short periods, e.g. half of the studies listed in Boardman et al. (2015) Table 1 are of less than 3 years duration.

Where erosion pins have been used to compare erosion/deposition rates on **contrasting surfaces** in the same area, the problem may well arise of accurate measurement where rates are low. Imeson (1971, 1974) compares rates on bare ground, where they are high, with much lower and presumably less reliable measurements from *Calluna* covered surfaces. A similar situation applies when using erosion pins on bajada surfaces (Wainwright et al., 2002).

Closely related approaches

Markers other than erosion pins may be more appropriate in some situations. At sites where erosion pins would be damaged or cause an obstruction, stakes may be driven into the ground adjacent to the area to be measured. These can then form a fixed base over which a rod or tape can be laid and measurements made at fixed intervals down to the ground surface, e.g. Tallis and Yalden (1983 p. 49). This is particularly appropriate for measures of damage to footpaths or trails. Horse impacts on Rocky Mountain trails are assessed by Summer (1986) and human impacts on paths on Box Hill, Surrey by Streeter (1975). This is analogous to the micro-erosion meter approach (High and Hanna, 1970). Hudson (1964) established metal pins set in concrete at ground level. Measurement of the distance to the ground surface were made by laying a portable aluminium rod on adjacent pins. A derivative of the traditional erosion pin, named a ‘dropper’, was used by Hancock and Lowry (2015).

A curious case of an ‘erosion pin approach’ is that of the Holme Post which records 130 years (1848-1978) of peat wastage in the East Anglian fens, UK (Hutchinson, 1980).

Comparisons of erosion pin results with those using other methods

Unfortunately, it is not straightforward to compare erosion rates derived from pins with rates derived using other methods, since what is being measured may not be the same.

A remarkable and fortuitous use of erosion pins is recorded by Hadley and Lusby (1967). Hillslopes in small catchments on the Mancos Shales were monitored using erosion pins. Measurements were made on the day before a high-intensity storm (28 mm in 6 h; 21 mm in 30 mins) and they were repeated on the following day. The average rate of loss from 5 slope profiles was 3.7 mm. Loss from the hillslopes based on erosion pin measurements were compared to the increase in volume of a small delta in a nearby reservoir and found to be closely comparable.

In a similar vein, Boardman et al. (2015) offer two ‘partial validations’ of erosion pin results: one uses depth of ^{137}Cs at pin sites and the other compares sediment yield from a badland area to estimated erosion using erosion pins.

Sirvent et al. (1997) compare erosion pin rates on erosion plots with sediment yield recorded by collector devices, the latter giving higher rates. Benito et al. (1992) report similar results from erosion pins and a microtopographic profile gauge. Hancock and Evans (2010) found good relationships when comparing erosion pin measurements with gully aggradation/degradation, and Hancock et al. (2008) compared a range of soil erosion measurement and modelling methods, including erosion pins.

The problem of measurement error

No scientific data are free from uncertainty. Thus, any scientific study must consider the error in the measurements which contribute to that study. Studies that aim to quantify soil loss or accumulation by using erosion pins are no exception.

However, early erosion pin studies were (with no exceptions) silent regarding measurement error. This was acknowledged by Lawler who in 1993 (p807) stated that ‘a clear need for research on the nature and magnitude of attendant errors exists’. For example, Imeson (1971) considers pin measurements ‘accurate to the nearest 1 mm’; Benito et al. (1992) mentions ‘potential measurement errors of 1 mm’; and Sirvent et al. (1997) states that ‘the accuracy of erosion pins is +/-0.5 mm’. None of these explains how their estimates of error were obtained. Other studies say nothing regarding pin measurement error: this is particularly problematic when erosion rates are low and calls into question the reliability of conclusions drawn e.g. Lazaro et al. (2008). Hancock and Lowry (2015) also quote very low rates from erosion pins: however, they validate these figures using rates from ^{137}Cs studies.

Error in the measurement of the exposed length of an erosion pin may be considered in terms of accuracy (closeness to some ‘true’ value) and precision (scatter of multiple measurements). Unfortunately, we do not and cannot know the ‘true’ value of the exposed length: the best that we can do is to assume that several measurements of exposure on the same pin ‘bracket’ (i.e. form a distribution around) this unknown true value: cf. the definition of the normal distribution. However, we can easily estimate precision by making repeated measurements of exposure on the same pin (see below).

The error inherent in pin measurement may also be classified as random or systematic. One source of systematic error in erosion pin measurement probably relates to the individual doing the measuring: different people may well perceive the exposed length in slightly different ways, particularly where the surface of the soil at the base of the pin is irregular and/or somewhat diffuse. This may occur, for example, where soils are stony and moving stones pile up behind pins. Such systematic errors can be reduced by having all workers adopt shared conventions, e.g. if the exposed length is noticeably different on different sides of a pin, then measure the maximum and minimum exposure and average the two measurements. All workers should also adopt a shared convention re. pins which become buried: if subsequently found by exhumation, do you measure the pin and then recover, leave exposed, or replace? (Greg Hancock, pers. Comm. 2016).

Boardman et al. (2015) carried out an experiment to quantify pin measurement error on their Karoo study sites. Ten re-measurements of each of the 25 pins at one site were carried out by the same person (Figures 3 and 4). 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. This was interpreted as an estimate of RMS error, i.e. the uncertainty which results from unavoidable and unpredictable random measurement error. Greg Hancock (pers. comm. 2016) carried out a similar procedure.

Figure 3: Error test.

Figure 4: Measurement of distance from ground surface to top of pin.

A currently unpublished follow-up experiment by Boardman et al. aimed to explore systematic error in pin measurement. A similar procedure was followed, but with three different people making measurements on the same pins. Here, RMS error for each person's measurements varied between 1.5 and 2.5 mm. Interestingly, there was little correlation between the magnitude of each person's RMS error, and the number of years of field experience of that person. There was some indication that measurements on particular pins made a larger-than-average contribution to overall scatter. But these 'troublesome' pins were not the same ones for each of the three individuals making the measurements.

It is instructive to compare the above estimates of unavoidable error in pin measurements with the error estimates cited by earlier work (see above). Earlier estimates appear, in the light of these results, over-optimistic. Change in the exposure of a single pin between two measurement dates may be very small. Thus, an RMS uncertainty of c. 1.5 mm implies that there can be little confidence in any conclusions drawn when summed or individual changes of pin exposure are comparable with the RMS error. This situation is likely, if the method of analysis involves short time intervals between pin measurements and/or measurements from single pins or relatively few pins. In such cases, there is a strong likelihood of the erosion or accumulation 'signal' being drowned in the 'noise' of measurement uncertainty. Conversely, results derived from analysis involving large totals of change in exposure depth, derived from summed measurements over many years and/or from many pins, inspire greater confidence: this has implications regarding the spatial and temporal scales for which erosion pins are a useful, yet still practical, approach.

Analysis of results from erosion pin data

Most commonly, the arithmetic mean of measured change in pin exposure is used to quantify net erosion or net deposition at a site (Hancock and Lowry, 2015). Changes in pin exposure (e.g. positive values for increased exposure, negative values for decreased exposure) are summed for all pins, and divided by the duration of observations. This procedure gives an average rate of net erosion or net deposition (in units such as mm/yr) for the area covered by the erosion pins and for the whole period of measurement.

This is the simplest possible approach to the analysis of erosion pin data. However, the above discussion of pin measurement error suggests that this simplest approach is also the most efficient, in terms of maximizing the confidence which may be placed in conclusions drawn i.e. in maximizing the contrast between measurement 'signal' and unavoidable measurement 'noise'.

Nonetheless, a simple net rate of erosion or deposition for the area of the pin grid is a rather limiting result in terms of the conclusions that may be drawn from it. We may well wish to also know (for example) what role extreme rainfall events played in land-surface changes on the site: an answer necessitates analysis of temporal subsets of the erosion pin data, with a correspondingly diminished confidence in any findings. Or we may be interested in spatial patterns of erosion and accumulation within the grid of pins: cf. the maps of erosion based on erosion pin measurement on plots in Scoging (1982), the 'ground lowering contours' of Sirvent et al. (1997), and Figure 5 (in which the downslope end of each site is at the bottom of each map; erosion pins are marked as dots; units of elevation change are mm. Erosion is positive, and indicated by darker shading; accumulation is negative, and indicated by lighter shading. The zero - i.e. no change - contour is thicker than other contours).

It is tempting (and relatively easy, with a modicum of GIS skill) to produce such maps, which may appear impressive at first glance. But confidence in each data point of the map decreases as the number of pin

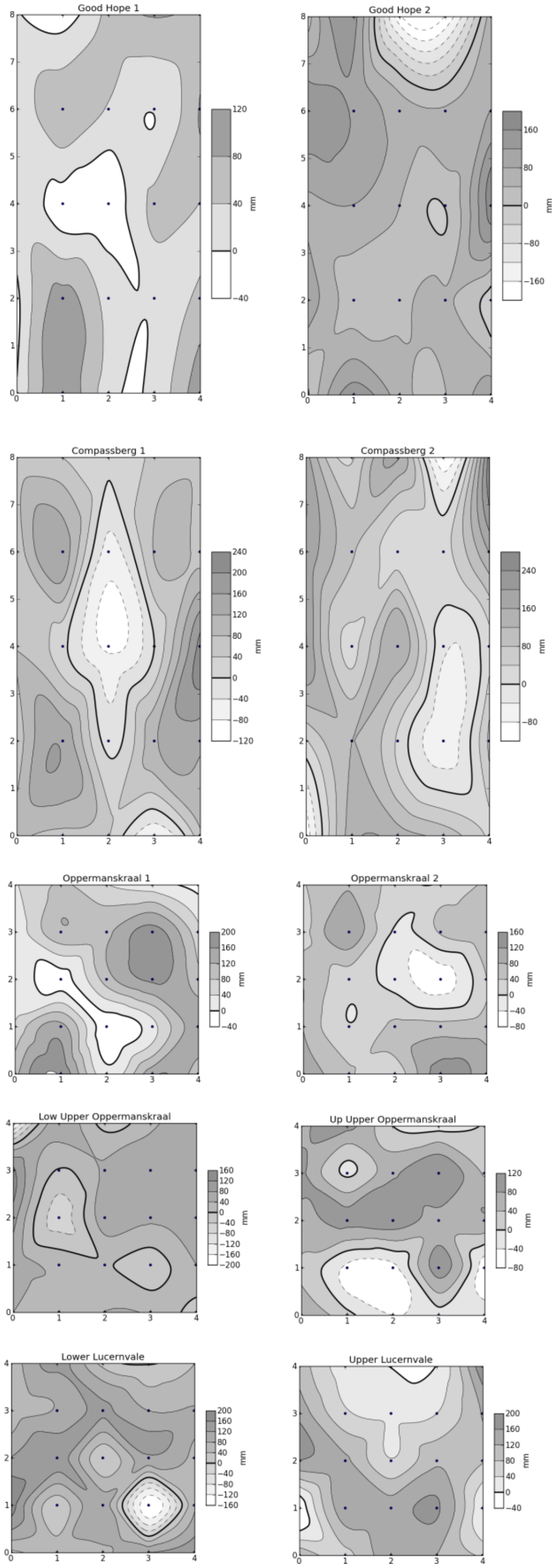

Figure 5: Spatial patterns of total change in elevation on ten erosion pin sites in the Karoo, South Africa, during 13 years of monitoring

measurements used to generate that point's value decreases. Spurious values (i.e. meaningless values of erosion or accumulation due to the pin measurement 'signal' being overwhelmed by measurement error 'noise') at data points can easily -- depending on the spatial interpolation algorithm used -- create maps which are wholly illusory.

A different set of problems arises once we desire to set pin results in a wider spatial and/or temporal context. The validity of so doing depends on choices made during the siting of the pins (see above) and will not be discussed further here.

Recommendations

Planning the study

- The aims of the study should be clearly articulated before placing any erosion pins. The aims will influence the location of pin sites, the placing of individual pins, the duration of the study (e.g. on badlands, this must be long enough to include a sufficient number of high-magnitude, low-frequency weather events), and the measurement interval.
- Erosion pins are not suitable where regular disturbance is occurring such as on cultivated land, or where slope evolution is dominated by mass movements such as cliffs, river banks and gully sides. It is difficult to establish the amount of retreat or loss when the pin itself is regularly lost.
- Initial installation of the erosion pins disturbs the surface: thus the first set of measurements may be atypical, and should be treated with care.
- A weather station adjacent to the erosion pin site is desirable.
- A GPS may be useful when revisiting pin sites after several months, particularly in remote areas.
- Many authors have commented on the problems of disturbance of erosion pins by frost heave, swelling and creep of soils and the need to take into account these natural processes.
- A choice is to be made between a large number of pins to obtain reliable estimates of average rates, for example for a hillslope; as against a few closely monitored or technically sophisticated pins

such as in using the PEEP system (Lawler, 1991).

- Measurement errors should be assessed (cf. Boardman et al (2015). Sites with low rates of erosion may not be suitable for erosion pin techniques because of measurement error.
- The nearby availability of other erosional data (such as rates of reservoir deposition) which may be compared with results from erosion pins may well add considerable scientific value to the study. Such comparison is not simple, however.

Figure 6: Paint spraying of pins.

Installing pins and making measurements

- Pins should be of sufficient length. Keay-Bright and Boardman (2009) and Boardman et al. (2015) successfully used pins of 335 mm length pushed into the ground about half their length.
- Regular spray-painting of pins prevents rusting and aids relocation (Figure 6).
- Care should be taken not to disturb the immediate area of the pin both at installation and at times when measurements are made.
- Pins that are lost e.g. through trampling or bank collapse may be replaced: this results in the loss of one set of measurements for that pin.

Analysis of results

- Because errors in pin measurement are not negligible (Boardman et al. 2015), there can only be confidence in results if long time intervals between measurement and/or results derived from many pins are considered. Results from single (or few) pins, over short time periods, run a very real risk of having the 'signal' lost in random noise.
- A convenient way of dealing with this is to analyse results so that that inferences are first drawn from analysis of the greatest number of pins and/or the longest period of measurement. There will be greatest confidence in these first conclusions. Subsequent analysis can focus on subsets of the data i.e. smaller numbers of pins and/or measurements from shorter time intervals. Confidence in these subsequent analyses will be lower.
- Estimation of average rates of erosion from pin sites may be carried out in different ways and involve different assumptions. These should be clearly stated. Most published literature is not clear on how average rates are arrived at.
- Great care should be taken in extrapolating from erosion pin results to larger areas: see for example Lawler (1993 p. 798).

Acknowledgements

Several people have over the years helped with our erosion pin measurements in South Africa, most notably James Keay-Bright, Ian Foster, Lisa Mol, Mark Williams and John Gates. We thank Tony Parsons and Ian Foster for useful discussion, and Greg Hancock and Tony Parsons for their very helpful reviews.

References

Benito G, Gutierrez M, Sancho C. 1992. Erosion rates in badland areas of the central Ebro basin (NE-Spain). *Catena* **19**: 269-286.

Besler H, Lancaster N, Bristow C, Henschel J, Livingstone I, Seely M, White K. 2013. Helga's dune: 40 years of dune dynamics in the Namib desert. *Geografiska Annaler A* **95(4)**: 361-368.

Birnie RV. 1993. Erosion rates on bare peat surfaces in Shetland. *Scottish Geographical Magazine* **109**: 12-17.

Boardman J, Favis-Mortlock DT, Foster IDL. 2015. A 13-year record of erosion on badland sites in the Karoo, South Africa. *Earth Surface Processes and Landforms* DOI: 10.1002/esp.3775.

Bridges EM, Harding DM. 1971. Micro-erosion processes and factors affecting slope development in the Lower Swansea Valley. In *Slopes Form and Process*, Brunsden D. (ed). Institute of British Geographers: London; 65-79.

Clarke ML, Rendell HM. 2006. Process-form realtionships in southern Italian badlands: erosion rates and implications for landform evolution. *Earth Surface Processes and Landforms* **31:** 15-29.

Clayton L, Tinker JR. 1971. Rates of hillslope lowering in the Badlands of North Dakota. North Dakota University Water Resources Research Institute, Report W1-221-012-71. W73.09121.N.T.I.S. PB 220 355. 1-36.

Colbert EH. 1956. Rates of erosion in the Chinle Formation. *Plateau* **28(4)**: 73-76.

Eckarrdt FD, Livingstone I, Seely M, Von Holdt J. 2013. The surface geology and geomorphology around Gobabeb, Namib desert, Namibia. *Geografiska Annaler* **95(4)**: 271-284.

Emmett WW. 1965. The Virgil Network: methods of measurement and a sampling of data collected. *International Association of Scientific Hydrology Publication* **66**: 89-106.

Evans R. 1967. On the use of welding rod for erosion and deposition pins. Modified depth gauge for erosion rod measurement. *Revue de Geomorphologie Dynamique* **17(4**): 165-166.

Evans R. 1977. Overgrazing and soil erosion on hill pastures with particular reference to the Peak District. *Journal of the British Grassland Society* **32**: 65-76.

Fanning P. 1994. Long-term contemporary erosion rates in an arid rangeland environment I western New South Wales, Australia. *Journal of Arid Environments* **18**: 173-187.

Godfrey AE. 1997. Mss movement of Mancos DShale crust near Caineville, Utah: a 30-year record. *Geografiska Annaler* **79A**: 185-194.

Godfrey AE, Everitt BL, Martin Duque JF. 2008. Episodic sediment delivery and landscape connectivity in the Mancos Shale Badlands and Fremont River system, Utah, USA. *Geomorphology* **102**: 242-251.

Hadley RF, Lusby GC. 1967. Runoff and hillslope erosion resulting from a high-intensity thunderstorm near Mack, western Colorado. *Water Resources Research* **3(1):** 139-143.

Haigh MJ. 1977. The use of erosion pins in the study of slope evolution. In, *Shorter Technical Methods (II). Technical Bulletin No. 18*, British Geomorphological Research Group. Geo Abstracts: Norwich, UK; 31-49.

Hancock GR, Loughran RJ, Evans KG, Balog RM. 2008. Estimation of soil erosion using field and modelling approaches in an undisturbed Arnhem Land catchment, Northern Territory, Australia. *Geographical Research* **46**(3): 333-349.

Hancock GR, Evans KG. 2010. Gully, Channel and hillslope erosion – an assessment for a traditionally managed catchment. *Earth Surface Processes and Landforms* **35**, 1468-1479.

Hancock GR, Lowry JBC. 2015. Hillslope erosion measurement – a simple approach to a complex process. *Hydrological Processes* **29**: 4809-4816.

Harvey AM. 1974. Gully erosion and sediment yield in the Howgill Fells, Westmorland. In *Fluvial Processes in Instrumented Watersheds*, Gregory KJ, Walling DE (eds). Institute of British Geographers: London; 45-58.

High C, Hanna FK, 1970. A method for the direct measurement of erosion on rock surfaces. Technical Bulletin No. 5, British Geomorphological Research Group, Geo Abstracts, Norwich, UK.

Higuchi K, Chigira M, Lee, D-H. 2013. High rates of erosion and rapid weathering in a Plio-Pleistocene mudstone badland, Taiwan. *Catena* **106**: 68-82.

Hudson NW. 1964. Field measurements of accelerated erosion in localised areas. *Rhodesian Agricultural Journal* **31**: 46-48.

Hutchinson JN. 1980. The record of peat wastage in the East Anglian fenlands at Holme Post, 1848-1978A.D. *Journal of Ecology* **68**: 229-249.

Imeson AC. 1971. Heather burning and soil erosion on the North Yorkshire Moors. *Journal of Applied Ecology* **8**: 537-542.

Imeson AC. 1974. The origin of sediment in a moorland catchment with particular reference to the role of vegetation. In *Fluvial Processes in Instrumented Watersheds*, Gregory KJ, Walling DE (eds). Institute of British Geographers: London; 59-72.

Jungerius PD, van der Meulen F. 1989. The development of dune blowouts, as measured with erosion pins and sequential air photos. *Catena* **16**: 369-376.

Jungerius PD, Verheggen AJT, Wiggers AJ. 1981. The development of blowouts in 'De Blink', a coastal dune area near Noordwijkerhout, The Netherlands. *Earth Surface Processes and Landforms* **6**: 375-396.

Keay-Bright J, Boardman J. 2009. Evidence from field-based studies of rates of erosion on degraded land in the central Karoo, South Africa. *Geomorphology* **103**: 455-465.

Kirkby AVT, Kirkby MJ. 1974. Surface wash at the semi-arid break in slope. *Zeitschrift fur Geomorphologie Suppl*. **21**: 151-176.

Lawler DM. 1978. The use of erosion pins in river banks. *Swansea Geographer* **16**: 9-18.

Lawler DM. 1991. A new technique for the automatic monitoring of erosion and deposition rates. *Water Resources Research* **27(8)**: 2125-2128.

Lawler DM. 1992. Process dominance in bank erosion systems. In *Lowland Floodplain Rivers: Geographical Perspectives,* Carling P, Petts GE. (eds). Wiley: Chichester; 117-143.

Lawler DM. 1993. The measurement of river bank erosion and lateral channel change: a review. *Earth Surface Processes and Landforms* **18**: 777-821.

Lazaro R, Canton Y, Sole-Benet A, Alexander R, Sancho LG, Puigdefabregas J. 2008. The influence of competition between lichen colonization and erosion on the evolution of soil surfaces in the Tabernas Badlands (SE Spain) and its landscape effects. *Geomorphology* 102: 252-266.

Livingstone I. 2003. A twenty-one-year record of surface change on a Namib linera dune. *Earth Surface Processes and Landforms* **28**: 1025-1031.

Nadal-Romero E, Martinez-Murillo JF, Vanmaercke M, Poesen J. 2011. Scale-dependency of sediment yield from badland areas in Mediterranean environments. *Progress in Physical Geography* **35**: 297-332.

Ranwell DS. 1964. *Spartina* salt marshes in southern England 11: Rate and seasonal pattern of sediment accretion. *Journal of Ecology* **52**: 79-94.

Schumm SA. 1956. Evolution of drainage systems and slopes in Badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin* **67**: 597-646.

Scoging H. 1982. Spatial variations in infiltration, runoff and erosion on hillslopes in semi-arid Spain. In *Badland Geomorphology and Piping*, Bryan RB, Yair A (eds). Geobooks: Norwich; 89-112.

Sirvent J, Desir G, Gutierrez M, Sancho C, Benito G. 1997. Erosion rates in badland areas recorded by collectors, erosion pins and profilometer techniques (Ebro basin, NE-Spain). *Geomorphology* **18**: 61-75.

Slaymaker HO. 1972. Patterns of present sub-aerial erosion and landforms in mid-Wales. *Transactions of the Institute of British Geographers* **55**: 47-68.

Streeter DT. 1975. Preliminary observations on rates of erosion on Chalk Downland paths. Presentation to Conference, Institute of British Geographers, Oxford.

Summer RM. 1986. Geomorphic impacts of horse traffic on Montane landforms. *Journal of Soil and Water Conservation* **41(2)**: 126-128.

Tallis JH. 1981. Rates of erosion. In *Peak District Moorland Erosion Study Phase 1 Report*, Phillips J, Yalden D, Tallis J. (eds.). Park Joint Planning Board: Bakewell, Derbyshire, UK; 74-83.

Tallis JH, Yalden DW. 1983. *Peak Park Moorland Restoration Project Phase 2 Report: Re-vegetation Trials*. Peak Park Joint Planning Board: Bakewell, Derbyshire, UK.

Wainwright J, Parsons AJ, Schlesinger WH, Abrahams AD. 2002. Hydrology–vegetation interactions in areas of discontinuous flow on a semi-arid bajada, southern New Mexico. *Journal of Arid Environments* **51:** 319–330.

Wiggs GFS, Thomas DSG, Bullard JE, Livingstone I. 1995. Dune mobility and vegetation cover in the southwest Kalahari Desert. *Earth Surface Processes and Landforms* **20**: 515-529.