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Improving the utility of erosion pins: absolute value of pin height change as an indicator of relative erosion

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A B S T R A C T

Erosion pins can be an inexpensive and intuitive method to estimate hillslope soil erosion and deposition. It is common practice to calculate annual erosion/deposition rates (also called ground advance/retreat or ground lowering) from pin measurements as the mean net change in pin height over a given area. However, many studies have found this net 'real number' change does not produce strong relationships with erosion rates estimated using other methods, or with variables expected to be highly correlated with erosion, calling into question the efficacy of this approach. Here we evaluate an alternative (or complementary) approach - using the absolute value of pin height change to capture the overall magnitude of soil movement as an indicator of erosion. We used measurements from erosion pins in experimental plots across different maize-bean production systems and forest-fallows in northern El Salvador to compare both the absolute and 'real number' change in erosion pin height against modeled erosion, related factors (e.g., slope and soil cover), and soil loss collected in erosion pits. We found that the absolute value of pin height change was strongly correlated ($r = 0.67$, $p < 0.01$) with erosion rates predicted from the Revised Universal Soil Loss Equations (RUSLE) and moderately correlated ($r = 0.82$, $p < 0.10$) with erosion measured in collection pits, while no relationships were found for the real number value. The absolute value was also strongly correlated with RUSLE factors related to slope and cover, while no correlations existed for the real number value. Statistically significant differences in RUSLE-predicted erosion were found between plots classified as having 'high', 'medium' and 'low' vegetative cover, and these differences were also detected using absolute value of pin height change. Conversely, such differences were not detected using the net real number value. We conclude that, when using erosion pins for comparative analysis between land management practices or monitoring changes in erosion over time, the absolute value of pin height change is likely a better indicator than net real number change. We encourage additional research using new and existing datasets to further evaluate the utility of absolute value of pin height change as an indicator of relative erosion.

1. Introduction

Erosion pins are an inexpensive method to estimate hillslope soil erosion and deposition used by numerous studies with varied success (Benito et al., 1992; Diaz-Fierros et al., 1987; Edeso et al., 1999; Haigh, 1977; Hancock and Lowry, 2015; Shi et al., 2011; Sirvent et al., 1997). Typically, narrow metal pins are inserted into the soil to a known depth in a grid or transect pattern along a hillslope, and the length of the pin protruding from the soil is measured at multiple points in time (Haigh, 1977). Most studies calculate annual erosion/deposition rates (also called ground advance/retreat or ground lowering) as the mean net change in pin height for a given experimental unit, usually given in mm yr^{-1}. This net change value, what we are calling a net 'real number' change, is often then converted to a unit mass per area (e.g., kg ha^{-1} yr^{-1}) using soil bulk density (e.g., Benito et al., 1992).

This approach has the obvious advantage of quantifying erosion/deposition rates at a relatively low cost, and intuitively it makes sense, but many studies have found that results calculated in this way do not have strong relationships with erosion rates estimated using other methods and models, nor with variables that one would expect to be strongly correlated with erosion, such as slope or precipitation. For example, a review by Haigh (1977) reported that several studies found no correlation between erosion pin measurements and topographic variables, including slope. Diaz-Fierros et al. (1987) did not find a

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relationship between soil erosion estimated from pins and that estimated by the Universal Soil Loss Equation (USLE) in northern Spain, and also noted a lack of correlation with slope. More recently, Hancock et al. (2010) found no apparent relationships between erosion/deposition patterns and hillslope position using erosion pins. Likewise, they found no correlation between pin data and caesium-137 (^{137}Cs) radioisotope concentrations (an indicator of soil erosion). Another recent study in Australia did not find statistically significant relationships between erosion pin data and topographic variables derived from high-resolution airborne laser scanning (ALS, also called LiDAR) or rainfall data (Hancock and Lowry, 2015).

The incongruence between erosion estimated from pins and other methods, and the apparent lack of correlation with erosion-related variables, calls into question the efficacy of the net 'real number' change in pin height as an erosion indicator, especially for comparative studies evaluating the treatment effects of different land-management practices. For example, in a location experiencing large amounts of soil movement, some pins will experience high rates of erosion while others will experience high rates of deposition between measurements. When the mean net change value is taken for a given experimental unit and measurement period, pins experiencing erosion and pins experiencing deposition will offset each other, and the final 'real number' change value is often near zero (Luffman et al., 2015). This can mask the magnitude of overall soil movement, and may explain the lack of correlations observed in the aforementioned studies. Other studies have noted that the spatial pattern of erosion pin data is more randomly distributed than that of erosion predicted by other methods (e.g., Shi et al., 2011), suggesting that in an erosive environment individual pins will experience both erosion and deposition at varying and random rates between measurements. In many cases, soil may move downslope in waves, and soil deposited at a pin in a given measurement period may be more available for transport during subsequent rain events (Hancock and Lowry, 2015).

An alternative (or complementary) approach to using the net 'real number' change in pin height is to use the absolute value of pin height change to capture the overall magnitude of soil movement, as proposed by (Couper et al., 2002). The absolute value treats positive and negative changes in pin height equally as a general indicator of soil movement, erosion activity and soil instability (Couper et al., 2002), thereby avoiding the challenges mentioned above.

We propose that the absolute value of pin height change offers a valid and underutilized indicator of soil erosion, and may be especially useful in comparative studies assessing the soil conservation potential of differing land management practices. Couper et al. (2002) explored how different methods of handling negative changes in erosion pin height (including an index of 'activity', or absolute value) affected erosion comparisons, but only for river banks. They concluded that the manner in which negative pin readings are treated greatly influences deductions about erosion, and that absolute value better captured relationships between erosion and environmental drivers such as temperature and precipitation (Couper, 2003). Luffman et al. (2015) used both mean pin height change (i.e., real number change) and the absolute value of change to study gully erosion and found that of the two, only absolute value was correlated with precipitation variables and showed significant differences between morphological settings.

Although the utility of the absolute value has been demonstrated in some systems, it has not been studied for comparing erosion activity as it relates to land management, especially for hillslope, sheet and rill erosion. We propose that the absolute value of pin height change offers a valid and underutilized indicator of soil erosion that may be especially useful in comparative studies addressing the soil conservation potential of land management practices.

In order to test this hypothesis, we compared the correlations of absolute and 'real number' change in erosion pin height with modeled erosion, related factors (e.g., slope and soil cover), and soil loss collected in erosion pits within experimental plots under five hillslope agricultural management systems of varying soil conservation potential. We also assessed differences in erosion between management treatments as predicted by the RUSLE and measured using each of the pin height methods.

2. Material and methods

2.1. Study area and experimental design

This study was conducted in northern El Salvador, in a region characterized as a steep mountainous mosaic of forest, forest-fallow patches, agriculture (primarily subsistence cultivation of maize, beans and sorghum) and pastures (Kearney et al., 2017a). Mean annual temperatures for the region are 22–26 °C and annual rainfall averages about 1985 mm, mostly falling between the months of May and October, with a pronounced dry season.

Erosion pins were installed on 25 experimental plots (12 × 20 m), separated into five treatments replicated across five farms. These plots were part of a larger study comparing ecosystem service provision under four maize-bean production systems – conventional (CONV), organic (ORG) and two 'slash-and-mulch' agroforestry systems (SMAS-1 and SMAS-2) – and a forest-fallow (FOR) reference site. Elevation of the experimental plots ranged from 624 to 866 m and slopes ranged from 19 to 40°, typical of the area. The 240-m^2 experimental plots were managed for three growing seasons beginning in April 2013. All plots were planted by hand (i.e., 'dibbling'), following common farmer practice in the region, which allowed pins to remain in place for all three years. A complete description of the experiment and its objectives can be found in Kearney et al. (2017b).

2.2. Erosion pins

Steel erosion pins (0.6 cm diameter, 40 cm length) were installed in the experimental plots in May 2013, prior to maize planting. Pins were placed in a grid pattern of 3 × 6 pins at 3 m spacing for a total of 18 pins per plot (Fig. 1). Pins were hammered into the soil perpendicular to the slope, leaving approximately 10 cm protruding from the soil surface, following recommended practices (Haigh, 1977).

Eight additional pins were installed in 2 × 5 m erosion collection subplots established within the larger experimental plots (Fig. 1). These subplots were installed on 6 of the cultivated treatment plots, 3 under conventional management (CONV) and 3 under a 'slash-and-mulch' agroforestry system (SMAS-1). Each collection subplot was bordered with metal sheeting protruding at least 10 cm vertically from the soil surface to prevent soil and other debris from entering the plot from above. Sediment was collected approximately biweekly from plastic-lined collection pits (approximately 1.8 × 0.5 × 0.5 m) located on the downhill edge of each subplot. Collected sediment was oven-dried for 24 h at 105 °C, sieved to 2 mm, and both the coarse and fine fractions were weighed and converted to Mg ha^{-1}. Data from one collection subplot was removed due to a failure of the metal border and substantial run-on into the collection pit from outside the subplot.

For this study, pin protrusion was measured in April 2015 (two years after installation) and again in February 2016, covering the entire 2015/16 rainy season. Pins were measured using a digital depth gauge (0.02 mm precision), and the mean overall change in pin height for each plot ($n = 25$) and subplot ($n = 5$) was calculated as both the real number value and absolute value of pin height change in mm over the entire 10-month period (i.e., the difference between the first and last pin measurement). Pins were inspected for damage or disturbance seven times throughout the season, and only pins that remained undisturbed for the entire study period were used in the final calculation. Pin data was further cleaned prior to analysis by removing extreme values, identified as measurements exceeding three standard deviations of the sample distribution of all undisturbed erosion pins.

The real number value was calculated as the change in pin height

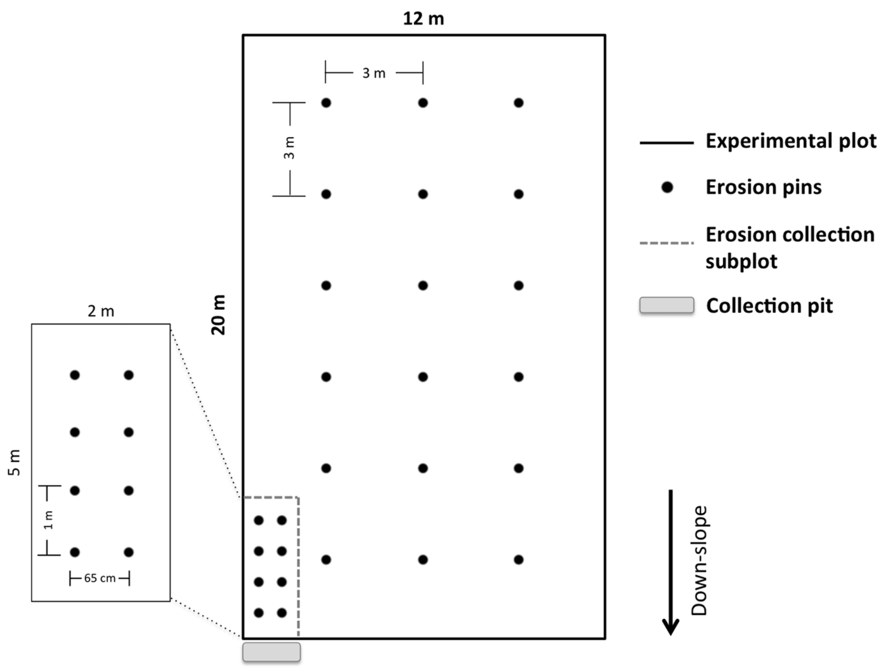

Fig. 1. Diagram of erosion pin setup.
The gridded layout of erosion pins within the experimental plot (18 pins) and erosion collection subplots (8 pins, inset).

over the measurement period and can be positive or negative. Positive numbers indicate erosion from around the pin (increased pin protrusion) and negative numbers indicate deposition. The absolute value is simply the extent of pin height change, or difference from zero (always positive). It indicates the magnitude of both erosion and deposition over the measurement period, but does not distinguish between the two.

2.3. Modeled erosion

We used data collected from the 240-m^2 experimental plots to develop erosion-prediction factors and model annual soil loss using the RUSLE (Renard et al., 1997) as:

$$A = R*K*L*S*C*P \quad (1)$$

where

A = annual computed spatial average soil loss, in Mg ha^{-1} yr^{-1}
R = rainfall-runoff erosivity factor
K = soil erodibility factor
L = slope length factor
S = slope steepness factor
C = cover management factor
P = support practice factor

The R factor was calculated following Renard et al. (1997) and using the equation from Brown and Foster (1987) cited within. Precipitation data was collected in 10-minute intervals from automatic tipping bucket rain gauges (Davis Instruments; Hayward, CA, USA; Model No. 7857) installed at each farm. The K factor was developed using the equation provided by Lim et al. (2011), converted to SI units (Renard et al., 1997). This equation requires the percentage of sand, silt and clay present in the soil, which was obtained from soil samples collected in each plot and analyzed at the CENTA (Centro Nacional de Tecnología Agropecuaria y Forestal) laboratory in El Salvador (see Kearney et al., 2017b). The L and S factors were computed from the slope length (20 m) and degree slope of each plot following Renard et al. (1997) and McCool et al. (1987) cited within. Slope was measured in degrees up- and down-slope from the center of each plot using a clinometer, and the average taken as the overall plot slope.

The C factor (cover management) was calculated based on canopy- and surface-cover subfactors (Renard et al., 1997). The canopy-cover subfactor (CC) was developed using the fraction of land surface covered by canopy and the average tree canopy height measured in each plot, as measured by Kearney et al. (2017b). The surface-cover subfactor (SC) was calculated from the percentage of land area covered by surface cover, using a surface roughness value of 0.80 (representing no-tillage) and a coefficient constant of 0.035, typical for cropland where rill and interrill erosion occur (Renard et al., 1997). A P-factor value of 1.0 was assigned to all plots, since no conservation practices were employed apart from cover management, which was already included in the C-factor.

2.4. Statistical analysis

We compared both the absolute value and net real number value of pin height change in each of the 25 experimental plots (excluding the pins in the collection subplots) to modeled annual erosion (A) using Pearson's correlation to assess the likelihood that each pin method is related to expected erosion occurring in the plot. We also checked the correlation with each of the RUSLE erosion-prediction factors to evaluate how strongly each pin assessment method was related to rainfall, soil, topographic and vegetation features. Both the absolute and real number values of pin height change across all plots were approximately normally distributed, as confirmed by Shapiro-Wilk tests and QQ-plots.

In addition to comparing pin data to modeled erosion in the experimental plots, we checked correlation with soil loss in the five erosion collection subplots. We calculated the Mg ha^{-1} of total soil (coarse and fine fractions combined) and sediment (fine fraction only, < 2 mm) collected in each pit during the 2015 rainy season and compared this with the mean absolute and real number pin height change for the pins located within each collection subplot. For correlation analysis, we used the *stats* package in R (R Core Team, 2016) to compute the Pearson's product-moment correlation coefficient (i.e., Pearson's r) and statistical significance of correlation (i.e., the p-value) for each variable combination.

In order to evaluate the utility of the absolute value and real number value to measure erosion, both were used in statistical analyses to detect differences in erosion between plots, as grouped in two ways: (1) by the five management systems described above and (2) by three cover classes reflecting 'high', 'medium' and 'low' vegetative cover, defined as the upper, middle and lower quantiles of C-factor classes across plots. While the five management systems are expected to influence vegetative cover, substantial variability occurred within treatments (e.g., tree densities, soil mulch biomass, weed pressure), and it was determined that vegetative cover should be isolated since it was expected to be the management factor most likely to influence soil movement.

A linear mixed effects model was run using the *lmer* package in R (Bates et al., 2015; R Core Team, 2016), with plot grouping (treatment or vegetation cover class) set as the fixed effect and farm location included as a random effect to account for site differences. The same statistical analyses were also performed using the RUSLE-predicted erosion rates for comparison. All significant differences were tested at $p < 0.05$, unless noted otherwise.

3. Results

Of the 450 pins initially installed in the experimental plots, 54 were removed due to suspected disturbance and 7 removed as extreme values. This left 389 pins in the final dataset, with each experimental plot retaining an average of 16 pins and no fewer than 11 pins. Only 5 pins were removed from the collection subplots: 4 due to suspected disturbance and 1 as an extreme value.

The absolute value of pin height change was strongly correlated with RUSLE-predicted annual erosion rates in the 25 experimental plots, while no relationship was found for the real number value (Table 1). Looking at the individual factors used in the RUSLE, we found a similar pattern. The absolute value of pin height change was significantly correlated with RUSLE factors and sub-factors related to slope and cover (i.e., LS, C, CC, SC), but not with the rainfall (R) or soil erosivity (K) factors; no statistically significant correlations were found for the real number value (Table 1).

For the five erosion collection plots, stronger correlations were also found for the absolute value of pin height change for both total soil loss and sediment (< 2 mm) loss (Table 2), although they were only significant at $p < 0.10$. A negative relationship was observed for the real number value change, but correlations were not statistically significant (Table 2).

We predicted erosion rates ranging between 23 and 76 Mg ha^{-1} yr^{-1} using the RUSLE in the experimental plots (240 m^2) and measured erosion of 0.6–2.1 Mg ha^{-1} in collection subplots (10 m^2), an order of magnitude difference. The smaller size and protected design of the subplots are likely responsible for much of this discrepancy, and when we changed the slope length of the RUSLE to reflect the subplot size, predicted erosion ranged from 3.3–7.3 Mg ha^{-1} yr^{-1} (data not shown). Erosion and deposition rate estimates calculated from the real number change in pin height and soil bulk density in experimental plots ranged from a loss (erosion) of 107 Mg ha^{-1} yr^{-1} to a gain (deposition) of 40 Mg ha^{-1} yr^{-1}, and these values were not correlated with predicted erosion (data not shown).

Table 1
Correlation of erosion pin measurement with individual factors of the RUSLE model.

Pearson's product moment correlation coefficients (*r*) for the mean absolute value (ABS) and real number value (RNV) of the average change in erosion pin height in experimental plots (n = 25) with individual factors from the Revised Universal Soil Loss Equation (RUSLE). Significance of correlation tests between paired samples are denoted as follows: *$p < 0.10$, **$p < 0.05$ and, ***$p < 0.01$.

Factor description	Factor	ABS	RNV
Rainfall factor	R	−0.216	0.224
Soil erosivity factor	K	0.064	−0.014
Slope length/steepness factor	LS	0.513***	0.077
Cover-management factor	C	0.535***	−0.17
Canopy-cover subfactor	CC	0.393*	0.115
Surface-cover subfactor	SC	0.398**	−0.235
Annual erosion (Mg ha^{-1} yr^{-1})	A	0.671***	−0.084

Table 2
Correlation of erosion pin measurement with soil/sediment loss in erosion collection subplots.

Pearson's product moment correlation coefficients (*r*) for the mean absolute value (ABS) and real number value (RNV) of change in erosion pin height in subplots (n = 5) with soil and sediment collected in pits. Significance of correlation tests between paired samples are denoted as follows: *$p < 0.10$, **$p < 0.05$ and, ***$p < 0.01$.

Material	Range (Mg ha^{-1})	ABS	RNV
Soil	0.6–2.1	0.815*	−0.338
Fine sediment (< 2 mm)	0.3–1.1	0.822*	−0.374

No significant differences were observed between management systems, regardless of the method used to predict or measure erosion (Fig. 2). Significant differences in RUSLE-predicted erosion were found between all three vegetation cover classes. Using the absolute value of pin height change, differences were detected between the 'high' and 'low' classes, although the 'medium' class could not be statistically distinguished from either of the other classes. No differences were detected between classes using the net real number value change in pin height.

4. Discussion

We found that the absolute value was strongly correlated with multiple erosion-related factors (in addition to RUSLE-predicted erosion), while the real number value showed no relationship with any factor (Table 1). Looking more closely at these results, we see that the absolute value captures interactions between slope and cover management, the variables driving erosion rates in the experimental plots. Absolute value was more strongly correlated with the cover-management factor (C) than with the individual subfactors used to calculate it (CC and SC), and an even stronger correlation was found for the final predicted annual erosion rate (Table 1). This observation that correlation was higher for factors derived from the interaction of other factors or subfactors further supports our hypothesis that the absolute value of pin height change can serve as a valid indicator of soil erosion.

We also found that the absolute value of pin height change was better able to detect significant differences in erosion between plots expected to have differing rates of soil loss, for example as a result of increased vegetative cover. While no significant differences were found between management systems, we did see a pattern of decreasing RUSLE-predicted erosion in tree-based systems (i.e., SMAS and FOR) that were expected to increase soil and canopy cover (Fig. 2a). This pattern was reflected in the absolute value of pin height change (Fig. 2b), but disappeared when using the net real number value (Fig. 2c). Increasing vegetative cover did significantly decrease predicted erosion and the absolute value of pin height change (Fig. 2d,e), indicating that management systems that increase vegetative cover sufficiently would, in fact, reduce soil loss. However, this reduction was not detectable when analyzing change in erosion pin height using the net real number value (Fig. 2f).

When using erosion pins for comparative analysis between land management practices or monitoring changes in erosion over time, the absolute value of pin height change is likely a better indicator than calculating the net real number change (i.e., ground advance/retreat). As reported by Luffman et al. (2015), we observed that individual pins experienced both erosion and deposition over time, indicating substantial soil movement, but the net change in pin height for any given measurement period appears to be episodic and random, suggesting soil deposited in one time period is often eroded in another. Given a long enough measurement period, it is expected that the net change in pin height would reflect actual erosion/deposition rates, but this period is unknown a priori and may be impractical for many research and monitoring applications. Since both erosion and deposition are

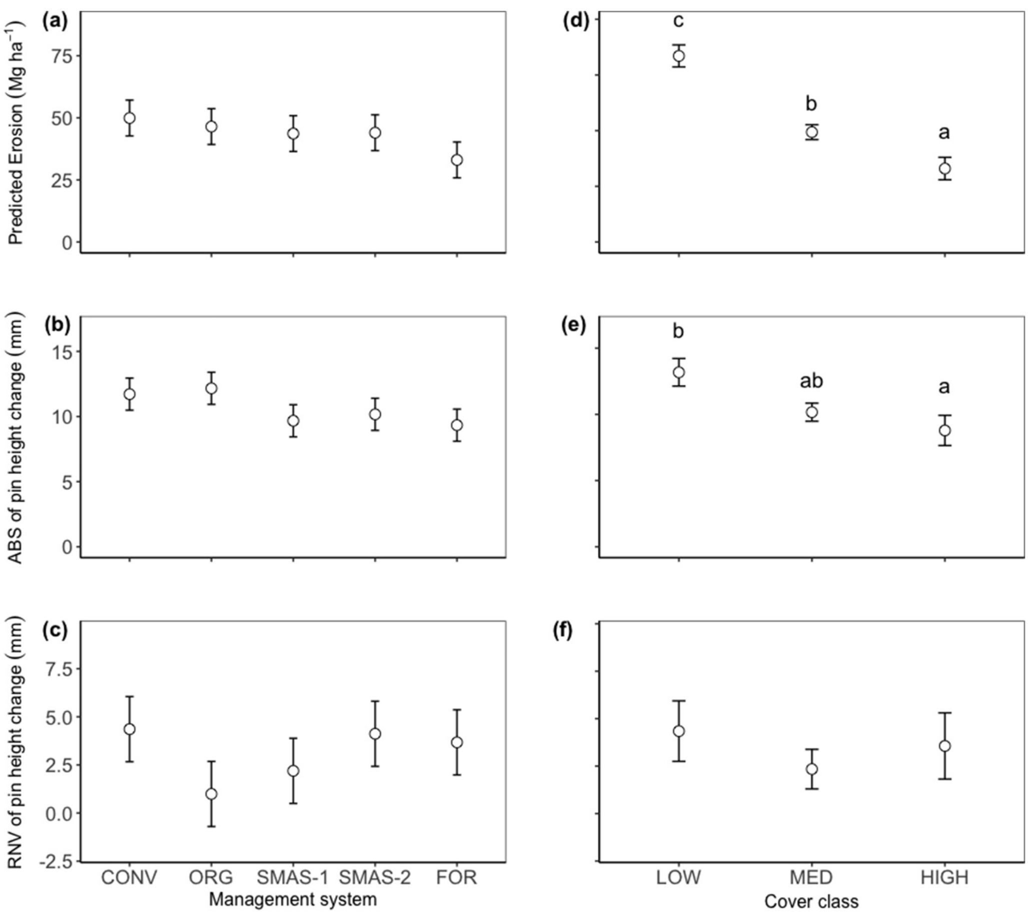

Fig. 2. Differences in erosion rates between management systems and cover classes. Relative erosion comparisons between management systems (plots (a)–(c)) and cover classes (plots (d)–(f)), using erosion predicted by the Revised Universal Soil Loss Equation (top row), the absolute value (ABS) of change in erosion pin height (middle row) and the real number value (RNV) of change in pin erosion pin height (bottome row). Error bars represent one standard error. Significant differences ($p < 0.05$) between categorical X variables are denoted by different letters. Points with the same letters are not significantly different and plots without letters had no significant differences. See text for an explanation of acronyms.

captured by the absolute value, it is important that pins are installed on relatively consistent slopes and are unlikely to experience deposition from a different land use upslope.

One argument against using the absolute value is that the ability to quantify erosion rates is lost. However, it may be possible to calibrate the absolute value of pin height change to measured erosion rates using other methods (e.g., collection pits or radioisotope concentrations) or modeled erosion rates (e.g., using the RUSLE) from a subset of plots or from suitable reference sites. For example, we could use the relationships between the absolute value of pin height change and RUSLE-predicted erosion, or sediment collected in pits, to predict erosion in similar locations using pin measurements alone. In our study, a small sample size means that the strength of these relationships for making such predictions is debatable. Additional research is needed to better understand the utility of calibrating erosion pins to accurately estimate erosion rates. The discrepancies between predicted erosion rates in our experimental plots and measured erosion in subplots highlights the need to carefully consider plot size and site conditions in future studies.

This study reiterates the conclusions of Couper et al. (2002) that negative pin readings require careful consideration and their handling should be both transparent and appropriate for the aims of the research. When comparing the soil conservation impacts of various land management practices and exploring relationships with drivers of hillslope erosion, we find the absolute value of pin height change is an effective handling method. We encourage other researchers to evaluate the relationship of the absolute value of erosion pin height change with erosion-related variables on existing and new datasets to corroborate or refute our findings that this method can serve as an improved indicator of relative erosion.

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