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ORIGINAL ARTICLE

A new approach to pedestal differentiation for soil loss estimation—a case study from a burnt area in north-central Portugal

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Abstract Soil pedestals have long been used as qualitative indicators of soil splash erosion. In rangelands, plant-capped pedestals, generally grass tussocks, have also been used to quantitatively estimate soil loss since the first half of the twentieth century. In agricultural lands, forests, and badlands, stone-capped pedestals have been used as qualitative and semi-quantitative indicators of active, 'extreme' erosion. Little work has been reported on using capstone pedestal data for quantifying soil loss. We postulate that three distinct capstone pedestal types may be present in any given location and that a detailed analysis of a pedestal height histogram may be used to recognize their populations. This analysis can subsequently inform if soil loss can be reliably estimated and if so, which of the existing methods using pedestal height data will provide more accurate results. The three proposed capstone pedestal types are: (1) neo-pedestals formed underneath surface stones exposed by (partial) removal of the soil surface cover; (2) endo-pedestals formed underneath stones that were buried in the soil but have been exposed by erosion; and (3) phoenix-pedestals formed underneath stones from collapsed pedestals. In the pedestal height histogram of any given location, a skew to smaller heights may indicate the existence of endo- and/or phoenix-pedestals, which may be revealed as a bi-(or tri) modal distribution when using a smaller bin size. This concept was applied to a case study where soil loss had been monitored for control plots and mulched plots during a 5-year period following wildfire in a eucalypt plantation. We measured pedestal heights and used methods to quantitatively assess soil loss from soil pedestal data in the available literature. Soil pedestal data at the end of the 5-year period under or overestimated soil loss in the control treatment, with results ranging from 60 to 115% of measured soil loss, depending on the method. It is postulated that phoenix- and endo-pedestals may be a driving factor behind the observed discrepancies. We discuss how future research may provide more insight into dominant processes, and how frequency distributions may be used to select the best methods for estimating soil loss from pedestals.

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Introduction

Pedestals as indicators of soil splash erosion have been reported since the first half of the twentieth century. Hendricks (1934) described soil pedestals held by grass roots and used the pedestal height to estimate the amount of soil removed in semi-arid south-western USA. Ellison (1947) published a series of experiments with a range of soils and described in detail how splashing raindrops act as erosive agents. He called soil particle detachment by raindrops "blasting", likening it to "the way that tiny dynamite explosions might be expected to loosen them", and estimated that a heavy rainstorm in an open, bare field may splash more than 250 tonnes of soil per hectare into the air. In a bare horizontal field with vertical rain and no wind, splash erosion would occur omni-directionally and not lead to soil loss or pedestal formation. Non-vertical rainfall, wind, and slope can give direction to splash erosion. Nevertheless, a proportion of splashed particles will always move along the contours or upslope. From directional factors, slope can cause removal of splashed soil particles by overland flow, leading to soil loss and increased rates of pedestal formation. In addition to slope, soil characteristics play an important role in pedestal formation, i.e., soil texture, structure, stoniness, organic matter content, and infiltration capacity. If pedestal heights can be used to accurately estimate soil loss, this would provide researchers and land users with a tool to (1) estimate soil loss with considerably fewer resources, or (2) allow substantially greater spatial coverage of erosion measurements than what is feasible with traditional monitoring using runoff/erosion plots. Plot-based erosion measurements are commonly very comprehensive and detailed and therefore, considerably time consuming and expensive (Robichaud and Brown 2002; Robichaud 2005).

Soil pedestals – sometimes also called "micro-hoodoos" (Slattery and Bryan 1992)—can be considered a 'niche' research topic in terms of the quantity of publications. During the last 44 years (1979 – 2023), for which electronic databases currently exist, only 26 publications have "soil", "erosion" and "pedestal" in the title, abstract, or keywords (SCOPUS). However, several ISI publications that use soil pedestals were missed with this method (i.e., Harden 1988; Poesen et al. 1994; Barthes and Roose 2002; Miura et al. 2003; Shakesby et al. 2003; Lazaro et al. 2008). Of the 26 ISI publications that feature soil erosion, and pedestals, only one has the word "soil pedestal" in the title (Santos de Jesus et al. 2022), suggesting that pedestals were never the main topic of research. At approximately one publication every other year, soil pedestals appear little researched, considering their common occurrence. Nevertheless, most land uses have been covered by quantitative soil pedestal research: grasslands (Hendricks 1934; Strickler 1961; Harden 1988; Basher and Webb 1997); croplands (Gburek et al. 1977; Okoba and Sterk 2006a, b); forests (Shakesby et al. 2003; Sidle et al. 2004; Anh et al. 2014); Badlands and bare mountain lands (Harris and Vita-Finzi 1968; Perez 2007; Keay-Bright and Boardman 2009). In their review on the effects of rock fragments on soil erosion, Poesen et al. (1994) considered that rock fragments on the soil surface could have ambivalent effects on soil erosion and urged caution in estimating soil loss from pedestal height data because of differential pedestal stability caused by capstone size, soil texture, slope angle, and other factors.

When soil pedestals are featured in publications, it is commonly as a qualitative indicator of where active soil erosion is taking place. Some authors consider that soil pedestals specifically indicate higher magnitude erosion events. Cole et al. (2020) found that burnt-only plots experienced higher erosion than burnt and logged areas, and attributed this to the larger raindrops under the burnt snags, which also induced higher and well-developed soil pedestals only in the burnt-only plots. Carlson (1952) wrote: "An extreme degree of erosion is indicated by the fact that in places rocks protectively cap pedestals of soil". Dissmeyer (1994) considered that soil pedestals were usually only visible when soil erosion exceeded 23 t/ha. Assuming a dry soil bulk density of 1.0 g/cm^3, i.e., every 1 mm of soil weighs 10 t/ha, this translates to a 2.3 mm soil layer. It should be noted that these values assume 100% bare soil, such as may occur in arable land use, and that in other land uses with spatially variable bare soil cover, such as grasslands or forests, pedestals can form at substantially lower overall erosion rates. Soil pedestals occur in two main cap types: plant-capped or stone-capped. Grass species normally form the cap in plant-capped pedestals, although pedestals can also form under other plant types such as silverworts (Perez 2007). Plant-capped pedestal height can overestimate soil loss because of pedestal growth from the top by soil particles that splash from the bare soil surface to the top of the pedestal where they are caught by the vegetation. Hudson (1993) observed several centimetres of grass-capped pedestal heights inside erosion plots that had measured negligible soil loss. Stone-capped pedestals are not sensitive to overestimating soil loss in this way since any soil particles that splash onto stone-capped pedestals will subsequently splash off again.

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Normally, qualitative soil pedestal data, often binary (yes/no), is used to inform the study methodology of a related topic, e.g., where to install equipment, or to interact with land users on erosion risk (e.g., Stocking and Clark 1999; Okoba and Sterk 2006a). Sometimes soil pedestals are used as semi-quantitative erosion indicators with classes of pedestal height and/or occurrence (e.g., Barthès and Roose 2002; Vigiak et al. 2005; Cole et al. 2020). Quantitative soil pedestal studies, i.e., where pedestal height is used to estimate soil loss, are less common and use a variety of methods. A common method for quantifying pedestal height is to take the mean of a population of pedestals (e.g., Anh et al. 2014), including when these data are used to estimate soil loss (Gburek et al. 1977; Sidle et al. 2004) or rainsplash erosion (Shakesby et al. 2003). The number of pedestals used to calculate the mean varies greatly, from three (Anh et al. 2014) to > 100 (Sidle et al. 2004). Some studies use a single locality per treatment, while others calculate mean values for several localities, which they then average into an overall average.

Stocking and Murnaghan (2000) recognised that stones inside the soil that become exposed by erosion and then continue to form capstones of soil pedestals will cause an underestimation of soil loss by the mean height method. To avoid this underestimation, they proposed the mean maximum height method, where the site (e.g., field) is divided into several localities (1 m^2) where the maximum pedestal height is recorded and subsequently averaged for the site. They did not indicate a minimum number of localities per site.

Stocking and Murnaghan (2000) proposed to estimate soil loss from soil pedestal data by multiplying the mean maximum pedestal height (mm) by the mass of a 1 mm soil layer (t/ha). To estimate soil loss (t/ha) for sites that do not consist only of bare soil, a common method is to first multiply the metric of pedestal height by the soil bulk density and then by the proportion of bare soil (Dissmeyer 1994). This method, therefore, assumes that soil only erodes from bare areas.

This study aimed to improve the accuracy of soil loss estimation from pedestal height data by selecting the most appropriate method based on the pedestal height histogram. Subsequently, the objective was to apply this approach to a case study that allows validation with plot-based soil loss measurements and soil cover data for a 5-year period following a wildfire in north-central Portugal.

Methods and materials

Study site

The study site is in a blue gum (*Eucalyptus globulus* Labill.) plantation in Sever do Vouga municipality, north-central Portugal. Immediately after a wildfire (26th and 28th 2010), a study was carried out to evaluate the effectiveness of forest residue mulching on runoff and soil erosion (Prats et al. 2014, 2016). Figure 1 shows an overview of the experimental treatments. Three treatment plots ($83 - 131$ m^2) were established, with a forest residue mulch application rate of 13.6 t ha^{-1} resulting in a soil cover of approximately 80%. Three similar control plots were also installed in a randomised block design together with the treatment plots. In addition, eight microplots (0.25 m^2) were laid out for both treatments at top, middle and bottom locations within the burnt slope. Erosion was monitored by collecting sediments using sediment fences for the large plots, and sediment and runoff in runoff tanks for the micro-plots. Five years after the wildfire when the runoff/erosion study was concluded, the present work on pedestals was carried out in the same plots. The main vegetation covering the site before the fire was the eucalypt plantation and some maritime pine trees (*Pinus pinaster* Aiton), which were cut and logged shortly before the wildfire occurred. Fire severity according to Keeley (2009) was classified as moderate, assuming the consumption of most of the undergrowth vegetation and the dominant black colour of the ashes. Logging just before the wildfire can be assumed to have destroyed any pedestals, and there were no traces of prior ploughing or other soil disturbances. Between the wildfire occurrence and the present study, there were no land use activities and the eucalypts had been left to re-grow from the stumps. The climate in the region is generally humid, with warm summers (humid mesothermal; Csb in Köppen classification). The mean (last 25 years) annual rainfall is 1609 mm and the mean annual temperature 14.9 °C (Ribeiradio weather station). In February 2011, four soil profiles were excavated along the slope, bottom to top. The results showed that sandy loam soils overlay pre-Ordovician

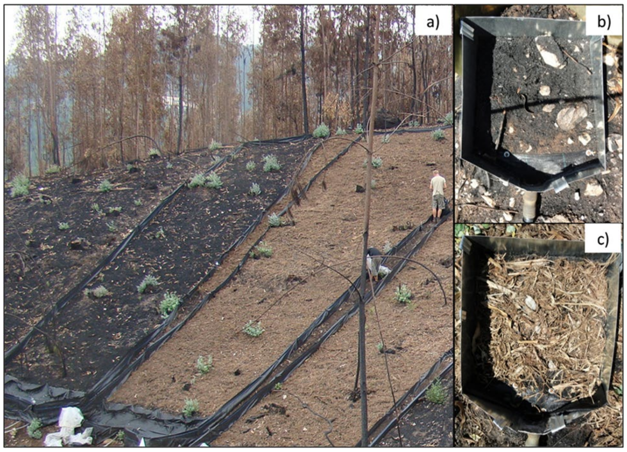

Fig. 1 The study area during the mulching day (14th September 2010): **a** sediment fence plots; **b** untreated and **c** mulched micro-plots (adapted from Prats et al. 2016)

schists, with 10.3% organic matter and a high topsoil stone content (55%) with relatively little spatial heterogeneity, i.e., ranging from 50.9 to 55.3% (Prats et al. 2014). At the bottom of the slope, the soils were classified as Humic Cambisols and at the top, as Umbric Leptosols (IUSS 2015). Further details are found in Prats et al. (2014, 2016).

Pedestal measurements and data analysis

For each untreated and mulched treatment, two sediment fence slope plots were sub-sampled at three localities (top, middle and bottom position), like the erosion microplot slope positions, avoiding any within-slope deposition areas. At each locality, a 1 m × 1 m grid and resolution of 10 cm × 10 cm was carefully placed on the soil surface of the sampling areas to determine the % ground cover by recording for each grid intersection one of five cover categories: bare soil, stones, ash (including charred plant materials), litter, and vegetation. Subsequently, the litter and vegetation were pruned carefully to expose the topsoil without damaging the pedestals. The grid was then placed again in the same position and a second ground cover description was made: stones (including rock outcrop), bare soil, ash (including charred plant materials), and mulch remains (in the case of treated plots). All pedestals in the grid were finally measured for height from the side facing the bottom of the slope using a ruler with a precision of 1 mm. Only pedestals > 1 cm in height from the soil surface to the top of the capstone, as well as capstones > 1 cm in diameter were recorded. In total, heights of 93 pedestals were recorded, 65 in the untreated and 28 in the mulched plots). The height threshold was a practical consideration in the field. The capstone diameter was selected to avoid capstone size influencing pedestal stability. Poesen et al. (1994) showed that for pedestals with a capstone > 1 cm in diameter, pedestal stability did not change with size.

Depth of soil loss

Soil loss in microplots was measured in g m^{-2} and converted to depth of soil loss (SLd) by applying the measured soil bulk density of 1.1 g cm^3 (Prats et al. 2016) to the method of Stocking and Murnaghan (2000) with the bare soil adaptation of Dissmeyer (1994) and corrected for the 55% stone (> 2 mm) content (Prats et al. 2016), according to Eq. 1:

$$\mathrm{SLd(cm)} = \frac{\left(\frac{SL}{BD}\right) * \left(\frac{100}{100-SC}\right)}{BSA} * 0.1 \tag{1}$$

where, SLd = soil loss depth in cm; SL = soil loss in kg m^{-2}; BD = bulk density in kg dm^{-3}; SC = stone content in %; and BSA = bare soil area as a fraction.

Table 1 shows the average soil loss from three SF untreated 100 m^2 plots and the four untreated 0.25 m^2 microplots for the first 5 years after the fire. Soil loss from the microplots was much larger than from the SF plots, attributed to the dependency of soil erosion on plot size. Missing data for years four and five was extrapolated from a two-phase power decay function fitted through the measured data of years one to three (Fig. S1), resulting in Eq. 2 with a robust standard deviation of the residuals of 40.34 (GraphPad Prism). It should be noted that year five consisted of only 8 months because of study termination.

$$\begin{aligned} Y = 2620 - 660.649 * \exp(-0.01269 * X) \\ - 1976.67 * \exp(-0.000535 * X) \end{aligned} \tag{2}$$

where, Y denotes soil loss (g m^{-2}) and X time (days).

Table 1 also provides the measured ash + bare soil cover for four of the 5 years (Prats et al. 2016), with the missing data for the fifth post-fire estimated as the average of the adjoining years.

Table 1 Depths of soil loss (cm) from measured soil loss (g m^{-2}) on the untreated microplots, according to Stocking and Murnaghan (2000). Microplot soil cover and soil loss (g m^{-2}) data are from Prats et al. (2016) for years 1–4, and from this study for year 5

Hydrological year	Rainfall (mm)	Maximum 30-min rainfall intensity (mm h^{-1})	SF measured bare + ash soil cover (%)		SF plots soil loss (gm^{-2})	Microplots soil loss (gm^{-2})	Estimated soil loss (cm)
1	1475	31	45		462	953	3.21
2	1186	27	30		92	299	0.26
3	2127	32	21		28	256	0.24
4	2171	14	13		25	192*	0.23†
5	1798	26	7		9	126*	0.20†
Mean	1893	26	19	Total	616	1826	4.14

*extrapolated from Prats et al. (2016); †estimate derived from extrapolated data; see Fig. S1

Results

Approach to improve soil loss estimation accuracy from pedestal population data

We postulated the existence of three types of soil pedestals differentiated by their formation that are important for their use in estimating soil loss: (1) phoenix-pedestals (the symbol of rebirth in Greek mythology) by genesis underneath stones from collapsed pedestals; (2) endo-pedestals (internal in Greek) by genesis underneath stones that were buried in the soil but since exposed by erosion; and (3) neo-pedestals ("new" in Greek) formed by pedestals underneath surface stones exposed by partial removal of the soil cover, e.g., vegetation removed by wildfire or ash/char removal by overland flow.

Selection of soil loss estimation method from histogram:

- No skewness and an approximate modal distribution, requires the mean or median height methods for accurate soil loss estimation; without skew, these metrics are identical. The 'mean maximum height' method (Stocking and Murnaghan 2000) could overestimate soil loss.
- A skewness to smaller pedestal heights, or a bi-(or tri-) modal distribution for a smaller bin size, likely caused by endo- and/or phoenix-pedestals, requires the Stocking and Murnaghan (2000) method of determining mean maximum height. The mean, and particularly median height methods, would underestimate soil loss.

Fig. 2 Examples of a stone-cap and char-cap pedestal at the study site

Case study from a burnt area in north-central Portugal

Figure 2 shows examples of stone-capped and char-capped pedestals found in the measurement grids. Not surprisingly, mulch-capped pedestals were only found in the mulched sampling grids. Char-capped pedestals were also only found in the mulch-treated grids with all visible char particles, including those on the soil surface, no longer present in the controls (Table 2). Char-mulch-capped pedestals formed 33% of all pedestals found in the mulched grids (10% char and 23% mulch). For stone-capped pedestals, the controls had approximately a three times higher density than the mulch treatment, i.e., 11.0 and 3.3 per m^2, respectively. Since the control treatment had 2.7 × greater average bare soil cover than the mulch treatment (Prats et al. 2016), stone-cap pedestal densities per bare soil were 57.9 and 47.1 per m^2 for the untreated and mulch treatments, respectively.

Mean and 'mean maximum' pedestal heights in this study of 93 pedestals ranged from 2.3 cm (mean in mulch plots) to 4.7 cm (mean maximum in untreated plots), with the largest pedestal measuring 8.0 cm (untreated).

Figure 3 shows the frequency distributions of capstone pedestal heights for untreated plots, and both capstone and char-mulch-capped pedestal heights for the mulched grid cells (all pooled data), at the end of the 5-year study. Pedestal heights were distributed as several discrete populations. Capstone pedestals in the mulch treatment showed an expected bimodal distribution in the controls, a trimodal distribution, although this may be an artefact of the above-mentioned absence of pedestals in the 4.0−4.5 category. Mulch-char-capped pedestals in the mulched treatment displayed a unimodal distribution with the same mode as the

Table 2 Performance of soil pedestal methods to estimate soil loss (cm) in the untreated plots

Method	Symbol	Height (cm)	Performance (% of calculated soil loss in cm)[a]	References
Mean pedestal height	$\overline{C}$	3.1	75	Gburek et al. (1977)
Median pedestal height	$\tilde{C}$	2.5	60	This study
Maximum pedestal height	C_{max}	8.0	193	This study
Mean maximum pedestal height	$\overline{Cmax}$	4.7	114	Stocking and Murnaghan (2000)
Mode of largest pedestal height population*		4.85	115	This study

*of more than three individuals (see Fig. 3); [a] = see Table 1

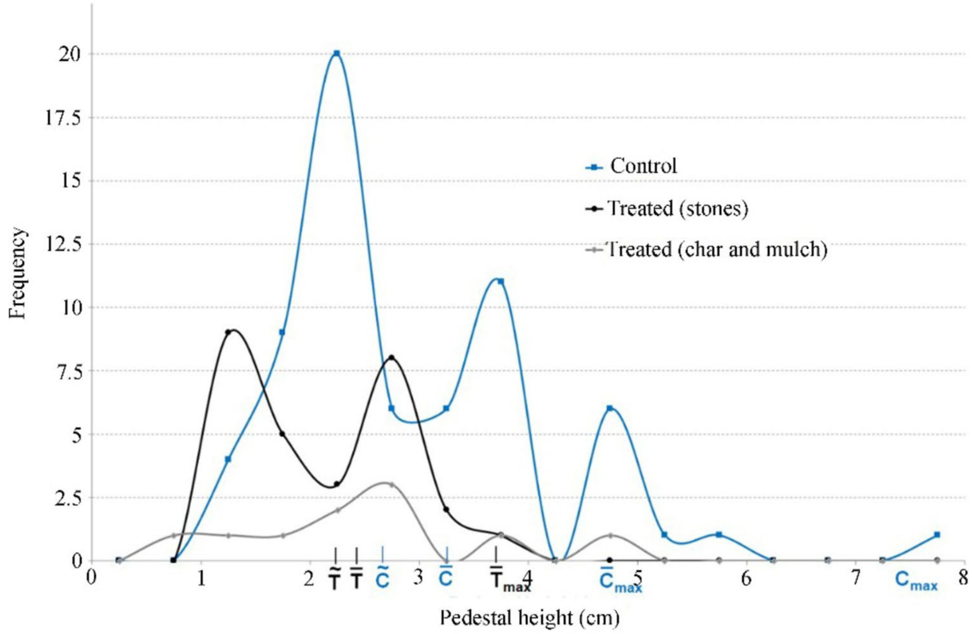

Fig. 3 Frequency distributions of pedestals in the untreated control (blue) and treated mulch plots (pooled data); mulched stone-capped pedestals are in black and char-or-mulch-capped pedestals in grey. $\overline{C}$, $\tilde{C}$, and C $_{max}$ indicate the mean, median, and maximum pedestal heights in control plots, respectively; $\overline{T}$, $\tilde{T}$, and T_{max} the mean, median and maximum pedestal height in the treated plots, respectively; $\overline{C}_{max}$ indicates the mean maximum pedestal height (Stocking and Murnaghan 2000) for the control and mulch treatments, respectively (see Table 2 for exact values and references)

taller pedestal population in the capstone pedestals for the same treatment (assuming a minimum of three pedestals per population).

In the mulch treatment, the stone-capped pedestals showed a similar distribution as in the controls, although with fewer pedestals and a shift to lower pedestal heights, the modes of the first two populations were 1 cm smaller. The lower number of pedestals was likely a result of the smaller bare soil area (range: 2–12%, mean: 6%).

Discussion and recommendations

Pedestal types by formation process

Phoenix-pedestals were first recognized by Poesen et al. (1994) who considered them a “pedestal cycle”. Phoenix- and endo-pedestals over estimated soil loss, i.e., skewed the distribution towards lower heights, or moved the mode of the distribution to lower heights. A histogram with a smaller bin size, observation numbers allowing, may show a bimodal distribution with a taller pedestal height population associated with neo-pedestals and a smaller one associated with endo- and/or phoenix-pedestals. Their relevance to soil loss estimation is the possibility to determine a lower limit to potential soil loss estimates from soil pedestal data.

Phoenix- and endo-pedestals cannot be easily identified in the field. It is possible that a proportion of them will have capstone orientations that are not along the slope, which may make them distinguishable from neo-pedestals. This has not been studied and an unknown proportion of phoenix- and endo- pedestals may have capstones along the slope, making distinction in pedestal type in the field uncertain. However, their occurrence can be determined by examining the pedestal height frequency distribution. In practice, this would mean that: where intercepted rainfall goes to the soil surface in larger drops from leaves or branches (Cole et al. 2020), this will show in the frequency distribution a second population of greater pedestal height, and consequently, induce higher soil losses. If this occurs in a negligible part of the study area, then the second population can be disregarded, and soil loss can be estimated from the mode of the larger population at a smaller pedestal height. If it occurs in a substantial part of the study area, then soil loss should be calculated separately for areas that are or are not affected by ‘interception dripping’.

In some cases, phoenix-endo-pedestals may exist: a pedestal formed underneath a capstone that eroded out of the soil, then collapsed and formed another pedestal underneath the same stone. Further research using dating methods or pedestal marking methods is required to validate the proportion of endo- to phoenix- pedestals, and the existence of phoenix-endo-pedestals.

Case study from a burnt area in north-central Portugal

The correction based on stones projecting 1.5 cm out of the soil, shifts the expected population closer to the measured one (dashed red line in Fig. S2). However, this correction moves the mode of the expected taller pedestal population further away from the measured heights, thereby overestimating it. Possible causes for this overestimation are: (1) during the first year, some pedestals collapsed and reformed underneath the same stone; (2) during the first year, stones buried in the soil were exposed and subsequently became capstones. The performance of various soil loss estimation methods from soil pedestal data against the calculated soil loss data are shown in Table 2. The confidence in the calculated soil loss for the controls is strong because missing data can be extrapolated from a strong regression (Fig. S1). The best estimates, 114% and 115% of the calculated soil loss, were:(1) the mean maximum pedestal height method (Stocking and Murnaghan 2000) which takes the mean maximum pedestal heights in the three sampling grids; and (2) the 'mode of the largest pedestal height population' method, which takes the pedestal height at the mode of the tallest pedestal population that has at least three individuals (48% of the calculated soil loss; (see also Fig. 3). The mean and median pedestal height methods substantially underestimated soil loss by 25% and 40%, respectively. The maximum pedestal height method, which estimates soil loss from the tallest pedestal found in any of the sampling grids, overestimated soil loss by 93%.

Post-fire pedestals have been proposed as indicators in the study area before (e.g., Martins et al. 2013; Cole et al. 2020), but this is the first quantitative study. Table 3 shows an overview of other pedestal height studies: 3.3 cm for a 10-year-long bare silt-loam soil in Vietnam (Anh et al. 2014); 2.4−3.1 cm a^{-1} for a 16-month observation of a clay-loam soil in Malaysia (Sidle et al. 2004), and 1−3 cm for a 15-month study of a light clay soil in Japan (Miura et al. 2003). However, more detailed comparison between studies is of limited value, considering that splash erosion is, among other factors, a function of soil texture and rainfall erosivity, which was different for these studies and ours. In addition, study duration is a major factor in comparing pedestal growth rates (Table 3), which may be because of pedestal dynamics or because of multiple-phase erosion rates, as observed in our study. Most of the soil was lost in the first post-fire year (78% of the 5-year amount). A study in New South Wales, Australia, by Shakesby et al. (2003), is the most relevant comparison since it was also carried out post-fire and had a similar soil texture and rainfall regime. However, a significant difference between the two studies was the duration, i.e., 5 years for this study and 6 months for Shakesby et al. (2003). After one rainy season (about 6 months) with 13−15 days of rainfall events of > 10 mm, a total of 1300 mm, on loamy-sand to sandy-loam soils, stone-capped pedestals were measured at 0.98−2.11 cm heights for mid-slope positions on two sites. The estimated 3.2 cm average soil loss after 12 months for this study (Table 1) is of the same magnitude, which builds confidence in the method of estimating pedestal height from measured soil loss and bare soil area data. Considering the difference in long-term mean annual rainfall, i.e., 900–1000 mm for their site and 1600−1700 for our study site (SNIRH 2015), pedestal formation rates may be of the same order of magnitude. The kinetic energy of rainfall in our study area is also relatively high, with > 100 J m^{-2} d^{-1} for rainfall during the most common weather (Fernandéz-Raga et al. 2010).

The char-mulch-capped pedestals in the mulch treatment showed only one population, with the same mode as the taller population of the stone-capped pedestals in the mulch treatment, but notably lacks a second population with a smaller mode (Fig. 3). Possible causes for this are: buried stones, which became exposed and underneath which

Table 3 Overview of quantitative pedestal height studies in forests

References	Pedestal descriptor	Location, average annual rainfall (mm)	Soil type	MP (year)	#P (n)	Pedestal height (cm)	Pedestal growth rate (cm a^{-1})	Measured soil loss (g m^{-2})	Estimated soil loss (cm)
Anh et al. (2014)	mean	Vietnam, 2268	silt loam	10.0	100	3.3	0.3	na	na
Sidle et al. (2004)	mean	Malaysia, 2654	clay-loam	1.3	100	2.4−3.1	2.1−2.4	na	na
Miura et al. (2003)	mean	Japan, ca. 2070	light clay	1.2	100	1.0−3.0	0.8−2.5	na	Na
Shakesby et al. (2003)	mean	Australia, 950	sandy loam	0.5		0.98−2.11	1.96−4.22	na	Na
This study, year 1	mean max[a]	Portugal, 1650	sandy loam	1.0	93	3.2	3.2	953	3.21
This study,	mean max[b]	Portugal, 1650	sandy loam	5.0	93	4.7	1.0	1800	4.14
This study,	mean[c]	Portugal, 1650	sandy loam	5.0	93	3.1	0.6	1800	na

MP Monitoring period; #P number of pedestals

[a] soil depth removal estimated from measured soil loss data for first year (Table 1)

[b] measured pedestal height after 5 years using the mean maximum method (Stocking and Murnaghan 2000)

[c] same as [b]but using the mean pedestal height

pedestals formed, contributed to the lower height stone-capped pedestal population. Since char particles were all on the soil surface, new pedestals could have been formed by exposure of buried char particles. However, the total number of char-mulch-capped pedestals is too low to be certain of this mechanism. In addition, pedestal collapse and reformation under the same capstone may have occurred in the mulch-treated plots as well, but there is no evidence to support this. The single pedestal in the 8 cm category appears to be a clear outlier, possibly a survivor of the logging operation.

Figure 4 shows how these types of pedestals may have formed in this study. Neo-pedestals are the commonly assumed type in soil pedestal studies. Usually, there has been a certain treatment or intervention, e.g., post-fire logging, in a forest or harvest crop followed by ploughing that ensures that the pedestals are not relics from a previous erosion period (paleo-pedestals) but formed since the intervention/treatment. This study indicates that stones that stick out of the soil surface at the time of treatment or intervention can result in an overestimation of soil loss from neo-pedestal height data. The recommendation therefore, is to measure the surface roughness and the stone cover, at the start of the treatment or intervention.

The likelihood of endo-pedestals resulting in an underestimation of soil loss was first described by Stocking and Murnaghan (2000) and led their recommending the mean maximum pedestal height method. In this study, their method produced the closest match to the soil loss estimates from measured soil loss data. However, the 'mode of largest pedestal height population' method was nearly equivalent. In situations of multiple-phase erosion response or bare soil areas, this method may estimate soil loss more accurately.

The implications of this study are that stone-capped pedestals as semi-quantitative or quantitative indicators of soil loss may substantially under or overestimate soil loss. This is contrary to plant-capped pedestals, which have been shown to typically overestimate soil loss (Hudson 1993). An examination of the frequency distribution can indicate which method is likely to provide more accurate results, and when pedestal collapse is likely to cause substantial underestimations and pedestal height data should only be used as a qualitative indicator of extreme erosion.

An interesting observation was the existence of char-capped pedestals only in the mulch-treated soils. The stone-capped pedestals reflect the sharp borders of the capstones (Fig. 2), indicating splash erosion as the dominant pedestal-forming process, relative to overland flow. Char-capped pedestals reflect the erratic borders of the char particle, with the char-cap sometimes overhanging the pedestal (Fig. 2), possibly reflecting a stronger overland flow component or weaker cap-to-soil connections. The low density of char (approximately 0.3 g/cm^3) and the position of char particles on top of the soil after a wildfire, make them susceptible to erosion. From post-fire erosion literature, we are not aware of reports of char-capped pedestals. The protection by the mulch, particularly in the first year, seems to have allowed some char particles to protect the soil sufficiently

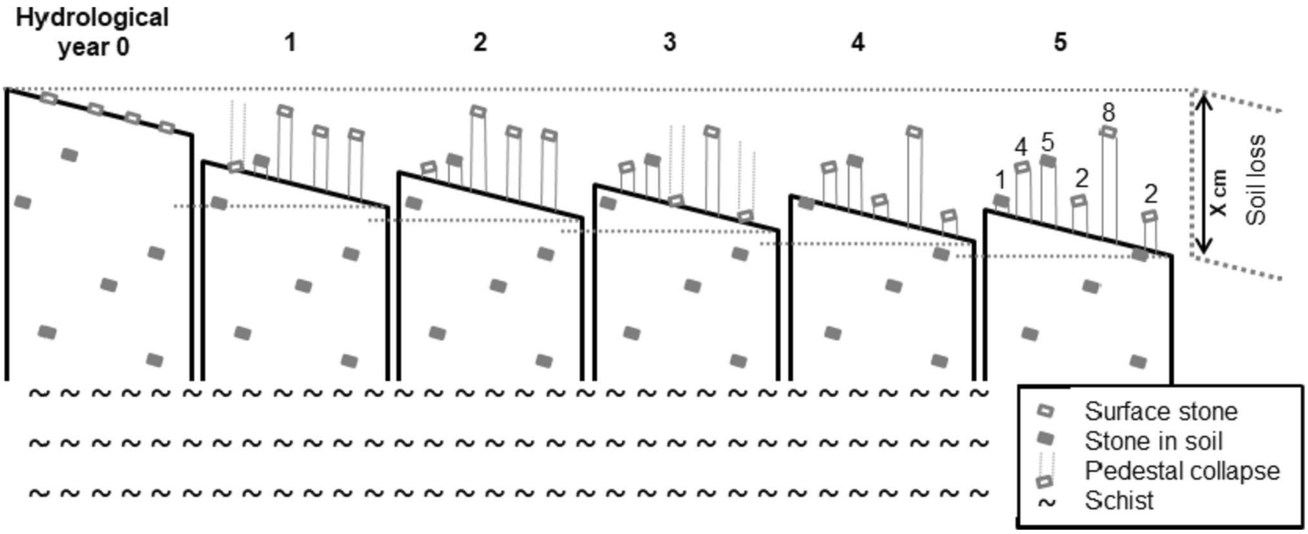

Fig. 4 Interpretation of pedestal formation/collapse dynamics in the bare soil parts of control plots. In year 0, the site was logged and assumed to have had no pedestals. For years 1–4, the soil pedestal dynamics are an interpretation of the authors to arrive at the pedestal height distribution in year 5 (Figs. 3 and S2). The interpretation is based on lowering the soil surface that was calculated from measured soil loss, bare soil cover (Table 1) and soil bulk density (1.1 g cm^{-3}; Prats et al. 2016), with interpolations to fill gaps (Fig. S1), stone cover data for year 1 (Prats et al. 2016) and year 5 (this study), and an approximation of pedestal half-life (Fig. 4). In year 5, pedestals of 2 and 4 cm heights are phoenix-pedestals, 1 and 5 cm heights endo-pedestals, and the 8 cm height is a neo-pedestal

to withstand splash and overland flow and remain in place to form pedestals. Further research is required to identify which mechanisms–physical, chemical, and/or biological, are responsible for this protective effect, and if char particle size plays a role. This is also of interest to biochar research, as it may indicate which particle size to use when biochar is used as an erosion mitigation measure (Prats et al. 2021). Previous work by Abrol et al. (2016) showed that biochar particles incorporated into the soil may protect it from erosion once they are exposed at the surface.

An increase in stone cover would support the existence of endo-pedestals. Unfortunately, this study was unable to determine with certainty that stone cover did indeed increase endo-pedestals. Stones were covered with ash and char after the fire, and as they were exposed by erosion, they may have become covered by litter and vegetation (see Prats et al. 2016). Future studies where stone cover is measured destructively by removing the ash/char layer, are required to determine if stone cover increases with erosion. This is also important for the possible self-limitation of splash erosion by increased protection of fine soil particles by stone lag (Shakesby 2011).

Conclusions

Three capstone pedestal types were proposed: (1) neo-pedestals formed underneath surface stones exposed by partial removal of the soil; (2) endo-pedestals formed underneath stones that were buried but have been exposed by erosion; and (3) phoenix-pedestals formed underneath stones from collapsed pedestals. In the pedestal height histogram of any given location, a skew to smaller heights may indicate the existence of endo- and/or phoenix-pedestals, which may be revealed by a bimodal distribution in a histogram using a smaller bin size, if observation numbers allow.

Our study allowed validation with monitored soil loss and soil cover data for a 5-year period following a wildfire. From this study, it was concluded that: (1) The ‘mean maximum pedestal height’ method (Stocking and Murnaghan 2000) estimated soil loss most accurately (114% of measured loss). The ‘mode of largest pedestal height population’ method was nearly equivalent. In situations of multiple-phase erosion or multiple-phase bare soil area, this method may estimate soil loss more accurately. The commonly used ‘mean pedestal height’ method underestimated soil loss (75% of measured loss), as did the ‘median pedestal height’ method (60% of measured loss). (2) Frequency distributions showed that at least two populations of pedestals were present in our study site, for a total of 93 pedestals. (3) Frequency distributions also indicated the possible presence of phoenix- and/or endo- pedestals. Pedestal types cannot be readily identified in the field. However, their occurrence can be determined by examining pedestal height frequency distribution. (4) Examination of the frequency distribution can inform which method is likely to give more accurate results.

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