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Effects of slope angle on mass movement by tree uprooting

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Abstract

An examination of 189 well-delineated mounds and pits in sandy soils of northern lower Michigan, all presumably formed by tree uprooting, was used to determine the effects of slope angle on morphology and volume, and to assess the potential importance of uprooting to mass movement. Slopes ranged from zero to 54%. Data indicate that mound and pit volumes increase with increasing slope angle, suggesting that on gentle slopes more of the disturbed soil wastes off the mound, back into the new pit. Mounds are often elongated in the downslope direction on steep slopes. Based on regression analyses, slopes of $\approx 47°$ are generally sufficient for all mound soil to slump or wash off in a downslope direction, rather than into the upslope pit. Thus, on steep slopes pit volumes provide a better representation of root plate volume. Pit depth can also be used as a surrogate for rooting depth on steep slopes where infilling from the mound is minimal.

1. Introduction

In forested areas, sediment transport by tree uprooting is a common process, and may, in many areas, be a dominant mechanism of mass movement (Denny and Goodlett, 1956; Mills, 1984). On steep slopes, trees are more likely to fall downslope (Hess, 1900), thereby transporting sediment attached to roots (the root plate) in that direction. Soil that slumps off the displaced root plate may form an adjacent mound of sediment and soil, resulting in a net downslope transport of surficial sediment. A pit, marking the former location of the roots, often is left as a marker of the former position of the tree, long after its bole has rotted away. Mound/pit pairs, widespread in forested regions (Stephens, 1956; Kooi, 1974; Ives et al., 1972; Beke and McKeague, 1984; Cremeans and Kalisz, 1988; Schaetzl, 1990), often cover nearly half of the forest floor (Collins and Pickett, 1982), underscoring the ubiquity of mass movement by uprooting. Schaetzl et al. (1989, 1990) have reviewed the soils and geomorphic literature on uprooting; the reader is referred to these compendia for a thorough discussion.

2. Theoretical considerations

The amount of soil displaced laterally and vertically during uprooting is a function of several variables: (1) slope angle, (2) angle and aspect of fall with respect to slope, (3) amount of backward rotation of the root plate during fall, and (4) volume of the root plate. This study examines the effects of slope steepness (angle; #1 above) on net downslope transport of soil material. We controlled for some of the other variables and assumed that the large size of the data set will render a clear trend or signal for interpretation.

We controlled for the "angle of fall" variable by using only mound/pit pairs in which the mound was

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directly downslope of the pit, when the pair was located on sloping terrain. Although backward rotation of the root plate during or shortly after fall may cause much of the soil to be effectively transported backwards into the pit (Schaetzl et al., 1989), this process is less likely to occur when trees fall downslope. Therefore, the potential role of this variable has been minimized, and the influence of variables (2) and (3) above, have been experimentally controlled for in this study.

Root plate volume (variable #4 above) is a function of several additional variables: (1) tree size, age and species (e.g. Mueller and Cline, 1959; Somerville, 1979; Coutts, 1983; Mills, 1984), (2) whether the tree was living or dead (Swanson et al., 1982; Cremeans and Kalisz, 1988), and (3) the tendency for the soil to adhere to the roots, which is, in large part, a function of (a) rooting pattern, (b) soil water content at the time of uprooting, and (c) soil texture. We controlled for the last variable by restricting the study to sites with sandy soils, which are nearly cohesionless when dry. We have no way of knowing or controlling for soil water content at uprooting or for variables (1) and (2) because of the time elapsed since the uprooting event and the disappearance of the bole. Thus, we have assumed that, if the data set is sufficiently large, the influence of the uncontrolled variables will become statistical residuals, error and/or "noise" around the true signal: effects of slope angle on mass movement volumes associated with tree uprooting.

The final aspect of theoretical concern to this study centers on erosion and disintegration of the root plate and mound/pit longevity. Ultimately, evidence of the uprooting event is lost as the root plate collapses into a mound/pit pair and is slowly levelled by surficial erosion processes. Schaetzl and Follmer (1990) studied several mounds developed in similar materials in northern Michigan and concluded that mounds can persist for 2000 years or more. Generally, older mounds are smaller than younger mounds (other things being equal) and, thus, the volumes of some old mounds underestimate the actual amount of material uprooted, of which an undeterminable amount has been moved downslope, away from the uprooting site (Fig. 2). Because all of the mounds we sampled showed no evidence of protruding wood or decaying boles, we assumed that they are all older than ≈ 150–200 years. By choosing only such "old" mounds, we controlled for age as best we could.

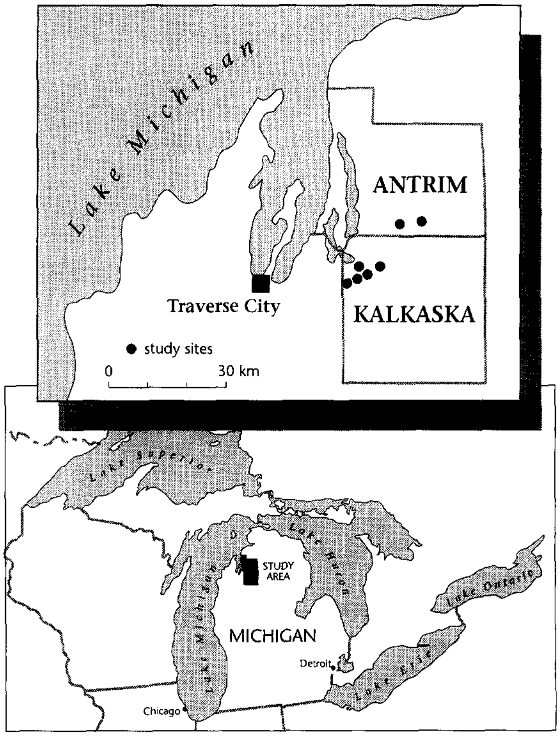

Fig. 1. Study area and study site locations.

This study attempted to isolate the effects of slope angle on mound/pit volume, assuming that other, uncontrollable variables would become statistical error and residual outliers, and act to weaken but not refute our trends and correlations. We acknowledge that mound/pit volumes are, at best, conservative surrogates for the actual amount of sediment disrupted and transported downslope by tree uprooting. They do, however, represent reasonable indicators of this geomorphically important process.

3. Study area and methods

Seven sites in northwestern lower Michigan, were selected for study. Five sites were in Kalkaska County and two in Antrim County (Fig. 1). In this region, slopes are developed in glacial drift, and are rolling to steep, with angles ranging to 60%. Each site generally spanned 2–5 ha, and was usually confined to a single geomorphic surface; kames comprised many of the landforms on which we conducted the survey. Widespread mound/pit topography is common to all these

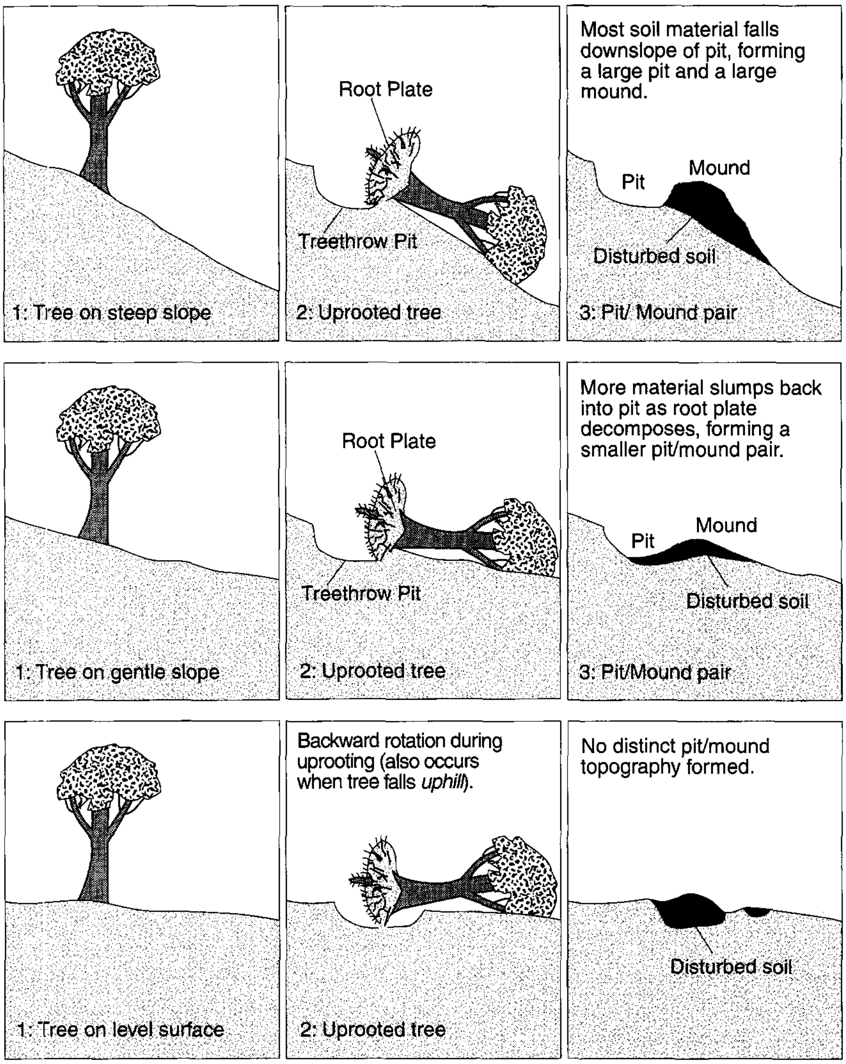

Fig. 2. Illustration of the deterioration of a mound/pit pair through time. The calculated mound or pit volumes will slowly diminish through time on gentle slopes, while on steep slopes mound and pit volumes will more accurately estimate the original root plate volume, even long after the uprooting event.

sites. The soils are predominantly Spodosols of sand and gravelly sand textures; all are well-drained. Each site has comparable, nearly mature, forest vegetation of sugar maple, beech, yellow birch and aspen.

We selected 189 well-defined pit and mound pairs for study, choosing only mound/pit pairs in which the mound was located downslope of, and immediately adjacent to, the pit. Although the sampling process was unsystematic, selection of only well-defined pit and mound landforms occurred to ensure that they were formed by treethrow, rather than the result of another surficial process (e.g., faunalturbation).

The slope position of each pit and mound pair was determined according to the nomenclature of Ruhe (1960). We obtained a minimum number of 26 pairs from each slope position: summit (26), shoulder (42), backslope (58), footslope (35), toeslope (28). Dimensions measured for each pit and mound include length, width and relief (depth for pits, height for mounds). In accordance with previous work on mound/pit dimensions (Denny and Goodlett, 1956; Kotarba, 1970; Putz, 1983; Mills, 1984), length was taken to represent the cross-sectional axis which runs parallel to the local slope contour, whereas width rep-

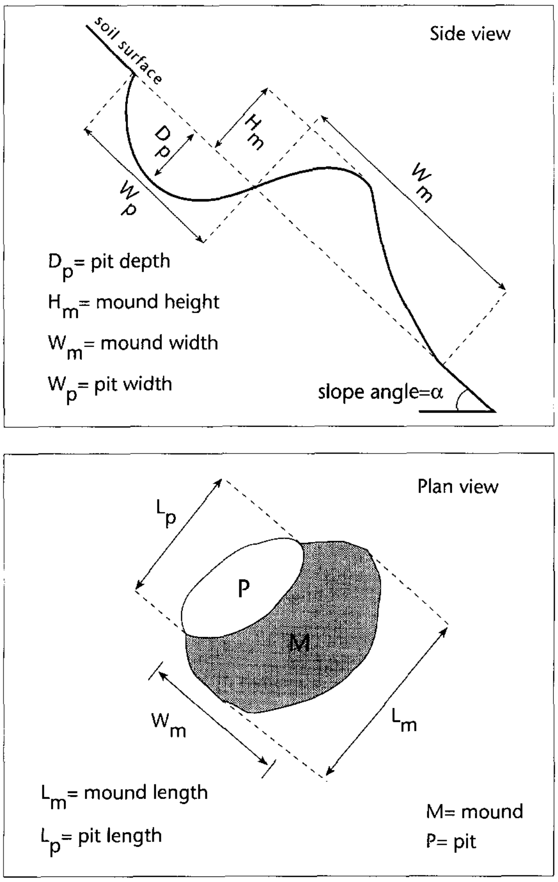

Fig. 3. Illustration of mound and pit dimensions used in this study.

resents the axis perpendicular to the slope contour (Fig. 3). To determine relief, a calibrated stake was positioned vertically in the bottom of the pit. Next, a rod, spanning the pit, was used to take readings of pit depth and/or mound height from the calibrated stake. The angle of the rod was made parallel with the angle of the slope (Fig. 3). Pit depth was considered the distance from the pit bottom to the rod; mound height was the vertical distance from the undisturbed surface (the surface of the ground was assumed to continue across the pit at the same angle as the slope) to the mound crest. Thick organic layers in pit bottoms posed some difficulties in obtaining accurate depth measurements. We removed some of the Oi horizon (composed predominantly of leaves and forest litter). Because the Oe–A horizon boundary is often diffuse, measurements were often taken from the top of the Oe, rather than the A, horizon. By contrast, organic soil horizons were thin or nearly nonexistent on the mound crest, and thus, readings were taken from the top of the A horizon at those locations.

We determined the mean angle of the local slope (%) near and downslope from each mound/pit pair as the mean slope between (a) the mound–pit intersection, and (b) a point 5–10 m downslope. This approach is especially significant for pit and mound pairs found on summit/shoulder and footslope/toeslope regions where the slope angle directly at the uprooting site may be substantially different from the calculated mean slope angle.

In order to calculate mound and pit volumes, we used an equation that assumes they have a shape that approximates half of an ellipsoid. The formula for half an ellipsoid in which the short axes are not equal is:

$$V=[2\pi(a/2)(b/2)c]/3 \qquad (1)$$

which can be rewritten as:

$$V=(\pi abc)/6 \qquad (2)$$

where V is the volume of half of a prolate spheroid (used here for mound or pit volume), a is the ellipsoid radius or semiaxis perpendicular to the direction of treefall (herein mound or pit length), b is the ellipsoid radius or semiaxis parallel with the direction of treefall (herein mound or pit width), and c is mound height or pit depth relative to the surrounding undisturbed ground surface, and is necessarily obtained as an ellipsoid radius or semiaxis (Fig. 3).

Although other researchers have used the ellipsoid (elliptical planes where the b and c axes may be unequal) or the prolate spheroid (circular planes for b and c with equal axes) approach to estimate mound/pit volumes, most have used the formula incorrectly or have employed inappropriate formulae. Denny and Goodlett (1956) used the prolate spheroid approach but forgot to halve the axes; thus the mound volumes calculated using their equation are much too large, ranging from 8.7 to 106.5 times larger than those calculated using Eq. (2) above. Mills (1984) had a problem with the b radius, and his approach yielded volumes that ranged from 0.7 to 13.1 times as large as ours. Kotarba's equation (Kotarba, 1970) for a prolate spheroid was correct but he neglected to halve the volume it calculated. Thus, volumes he calculated are two times too large. Putz (1983), in our estimation, used the "half prolate spheroid" formula correctly; hence, his equation yields volumes that are the same as ours.

4. Results and discussion

Theoretically, the volumes of the original root plate, the subsequent mound, and the pit volume should be equal. In reality, the actual (measured) mound volume is often less than the original root plate volume because of soil loss back into the pit and soil washed downslope. Pit volume may also be reduced from that originally formed by uprooting because of accumulated litter, plus any colluvial or wash materials from the mound and areas upslope. Although the last sediment source increases as slope angle increases (for trees that fell downslope), soil washing into the pit from upslope is, by and large, a very small input on the sandy slopes in our study area, and essentially can be ignored.

Because slumping and washing of soil into the pit from the root plate itself is lessened as slope angle increases (for trees that fell downslope), on steep slopes mound and pit volumes will closely approximate that of the original root plates. On gentle slopes much of the soil material in the original root plate may ultimately be transported back into the pit, from whence it came.

Mound and pit volumes both increase as slope angle increases. After attempting to fit linear and polynomial functions to the data, we noted that the observed relationships were invariably described best by power functions (Fig. 4). Pit volumes, which may closely approximate original root plate volumes for reasons mentioned above, increase more rapidly as a function of slope than do mounds. At a slope angle of 47.6°, calculated pit volume equals calculated mound volume (the interception point of the regression lines in Figs. 4A and 4B). Therefore, we suggest that slopes of $\approx 47°$ are sufficiently adequate for all the mound soil to slump or wash off in a downslope direction, rather than into the pit. For slopes steeper than $\approx 47°$ pit infilling is slow and accomplished primarily by sedimentation from sources upslope and by accumulation of organic litter. Small pit volumes on gentle slopes (Fig. 4B) result from pit infilling by sediment from the mound, as well as accumulated O horizon material. In their study of mass wasting by uprooting, Denny and Goodlett (1956) assumed that about half of the soil displaced by uprooting moves downslope (i.e., not back into the pit). The data presented above may be used in future studies of mass movement by treefall to refine this assumption for slopes $> \approx 47°$.

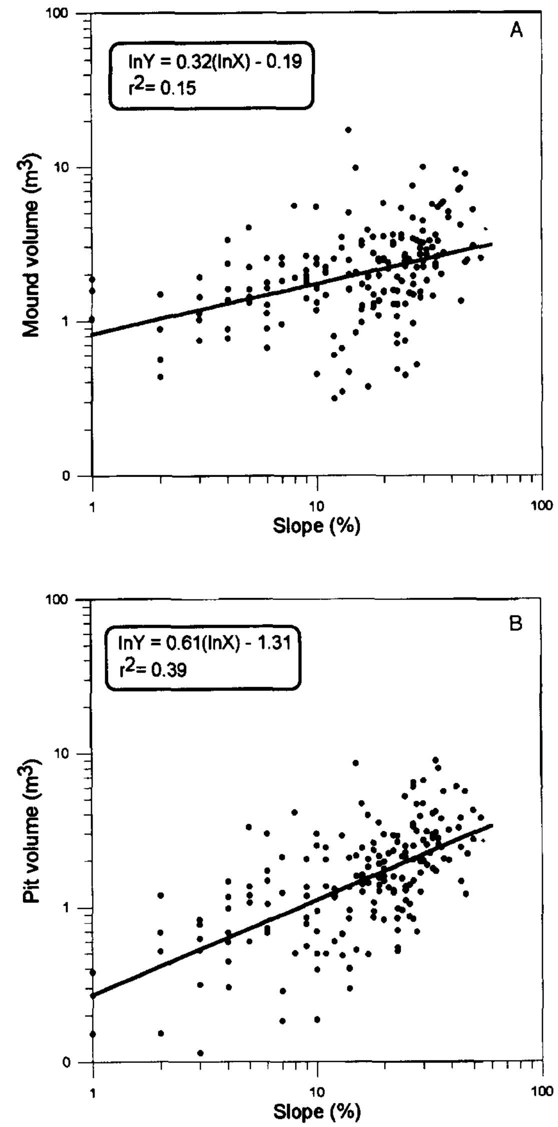

Fig. 4. Scatterplots illustrating mound volume versus slope angle (A) and pit volume versus slope angle (B).

Mounds tend to be elongated downslope where slopes are steep (Fig. 5), a finding that both confirms our supposition that on such sites pit volumes are a better representation of root plate volume, and also illustrates that downslope transport of sediment by uprooting is much more rapid on steep slopes. This relationship, as well as the data shown in Fig. 5, is also influenced by the difficulty we encountered in measuring mound volume, especially on steep slopes where the downslope soil/sediment apron is thin and long, making recognition and measurement of mound width

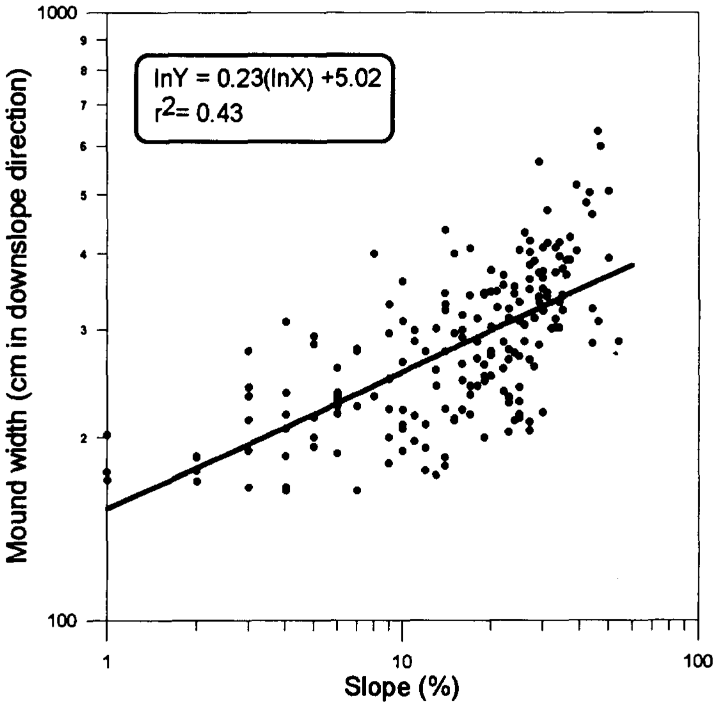

Fig. 5. Scatterplot illustrating mound width (measured as upslope–downslope distance) versus slope angle

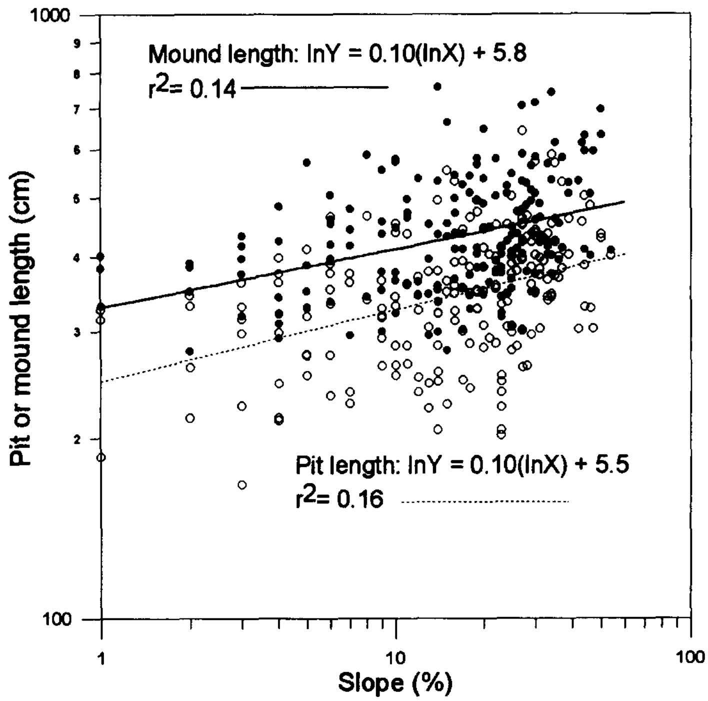

Fig. 6. Scatterplot illustrating pit and mound lengths versus slope angle.

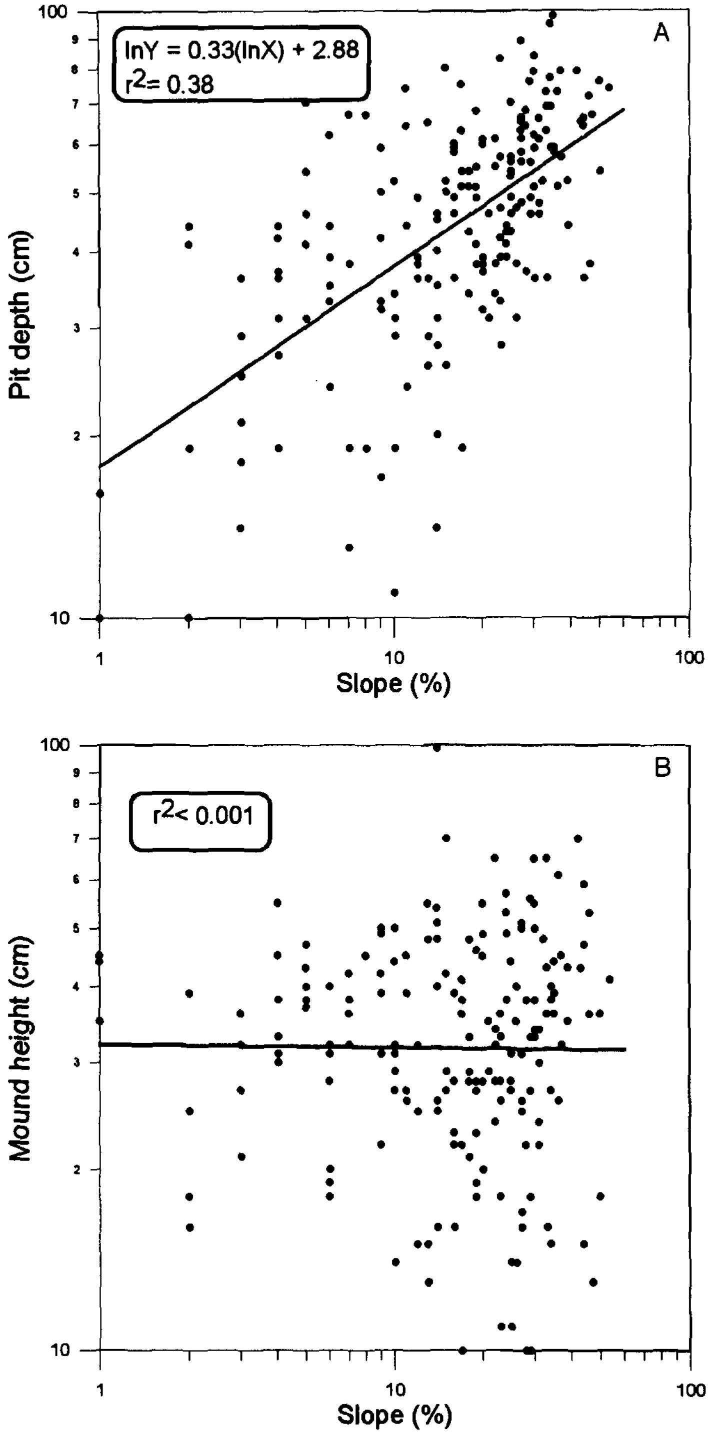

Fig. 7. Scatterplot illustrating pit depth versus slope angle (A) and mound height versus slope angle (B).

difficult (Figs. 2, 3). Elongated mounds, as well as our inability to accurately measure volumes, also accounts for pit volumes being larger than mound volumes on steep slopes. Normally pit volume cannot be larger than mound volume but on the steepest slopes we underestimated mound volume due to mass wasting of some mound soil downslope.

Pit and mound lengths weakly correlate with slope angle (Fig. 6). These data reflect root plate dimensions more directly than do pit and mound widths because infilling of pits from the sides (across the slope) is unlikely to be significant. Wastage of newly formed root plates, forming mounds, would cause the latter to appear to be longer than was the original root plate; this conclusion is supported by the data in Fig. 6, in which pit lengths are less than mound lengths for all slope angles.

Fig. 7A, which illustrates the relationship between pit depth and slope steepness, supports the contention that less root plate material is returned to the pit on steep slopes. It may also suggest that rooting is generally deeper on steep slopes, since the equation shows no sign of approaching an asymptote even at high ($>47°$) slope angles. Mound height, on the other hand, is not significantly affected by slope angle (Fig. 7B), although variability in mound height appears to be greater on steep slopes. These two relationships, when examined from a process viewpoint, suggest that mound height may be influenced by variables such as width of root plate and (particularly) age of the mound/pit pair, because mound height must decrease when examined over long periods of time. Bare or sparsely vegetated mounds present surfaces that are easily eroded by a variety of surficial processes, especially when slopes are steep. By comparison, pit depth may be strongly correlated with rooting depth, and on steep slopes where infilling from the mound is minimal, longevities may be great. Hence, the effects of age may be less important in explaining pit depth on steep slopes.

5. Conclusions

This study has shown that on progressively steeper slopes, treethrow becomes an important agent of mass wasting. We have assumed that the incidence of treethrow is roughly similar on all slopes. On steep slopes trees are more likely to fall downhill. Less material from the root plate will slump back into the pit, and the data suggest that little will end up in the pit on slopes $>47°$. Finally, because mounds tend to be elongated in the downslope direction as slopes steepen, soil/sediment on steep slopes, displaced by treethrow, will move substantially farther downslope before it becomes quasi-stabilized.

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