TREE UPROOTING: REVIEW OF TYPES AND PATTERNS OF SOIL DISTURBANCE

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Abstract: This paper reviews the processes of tree uprooting, examines the classification of pit and mound microtopography and assesses the effects of tree uprooting on soil mixing and genesis. The processes by which soil-horizon clasts are mixed as they slump off the root plate, and the ultimate patterns of soil horizonation within mounds, are primary foci of the paper. Longevity of treethrow mounds can exceed 2000 years, making these landforms more lasting features than is often assumed. Because of their great longevity, the pits and mounds formed by uprooting have lasting effects on soil morphology. Soils of these microsites often classify in different soil orders or suborders than do adjacent, less disturbed soils. The importance of tree uprooting to mass movement processes is examined. In some areas uprooting may be the primary mass wasting mechanism. Nonetheless, estimates of the amount of sediment moved and the net distance of transport vary greatly and may in some cases be overestimated. [Key words: pedoturbation, microtopography, pit/mound topography, mass wasting, geomorphology.]

INTRODUCTION

This paper reviews the formation and longevity of pit and mound microtopography formed by tree uprooting, and examines the importance of this process to mass wasting and soil genesis. Tree uprooting has an impact on both the physical

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and biological realms, but this paper focuses on the physical environment, concentrating on types and patterns of soil mixing and their impact on soil classification. Most examples are drawn from temperate forested environments. Previous reviews (Schaetzl et al., 1989a, b) have focussed on terminology, process, and the effects of uprooting on forest ecology and the environment. This paper provides the final (third) topical review of uprooting.

PIT/MOUND MICROTOPOGRAPHY

During uprooting of trees, a pit or depression is often formed, marking the former position of the roots (Lutz, 1940; Armson and Fessenden, 1973; Stone, 1975; Beatty and Stone, 1986; Schaetzl et al., 1989b). Soil slumps off the displaced and decaying root plate and may form an adjacent treethrow mound. Typically, pits and mounds occur as pairs and are widespread in forested regions (Stephens, 1956; Karpachevskiy et al., 1968; Kooi, 1974; Dwyer and Merriam, 1981; Ives et al., 1972; Beke and McKeague, 1984; Cremeans and Kalisz, 1988).

Although the initial size of the pit and root plate is a function of tree size and rooting habit, the eventual dimensions of the pit/mound pair are conditioned by the quantity of sediment that returns to the pit via slump and wash processes (Lutz, 1940; Putz, 1983; Beatty and Stone, 1986). Factors that affect the slump process include soil texture, structure, gravel content, freeze/thaw activity, precipitation regime, decay rate of the binding roots, and faunal activity within and on the surface of the root plate (Lyford and MacLean, 1966; Putz, 1983). The amount of soil which washes into the pit is often related to ground slope. On gentle slopes more soil returns to the pit, partially or completely filling it (Goodlett, 1954; Schaetzl and Follmer, 1990). On steep slopes uprooted trees usually fall downslope (Hess, 1900; Cremeans and Kalisz, 1988) and much of the soil that slumps off the root plate is deposited downslope, rather than in the upslope pit.

Several authors have defined microsites of pit/mound topography. Burns (1981) divided the forest floor into areas characterized by pits, mounds, or zones of recent stability. Hutnik (1952) identified four such sites: depression or pit, upper surface of the root ball (former soil surface), top edge, and lower surface of the root plate. Stone (1975) described the side of the pit/mound pair on which the tree fell as the throw side and the opposite side as the take; Small (1987) referred to mound sides as distal and proximal to the pit (see also Schaetzl et al., 1989b). The terminology used should be adjusted to the type of study undertaken. For example, studies concerned with micro-scale variations of vegetation, soils, or climate within the region of a pit/mound pair may prefer Hutnik's (1952) terminology, whereas Burns' (1981) usage is more appropriate for more general studies.

Pits and mounds can be further classified on the basis of shape. Simple treefall usually results in ovoid pits, while slight backward displacement during treefall may form crescentic pits (Beatty and Stone, 1986). Partial backward displacement of the root mass may lead to the formation of two small pits on either side of a mound (Nielsen, 1963), whereas complete backward displacement may form a pit on the lee side of the mound, potentially complicating later determinations of treefall direction (Lutz and Griswold, 1939; Schaetzl et al., 1989b). Nielsen (1963) ascribed the latter process to trees falling against nearby standing trees, or to boulders acting as pivots near the tree base, or to trees falling uphill.

Mound distinctness, measured as slope of the mound sides or relief from mound crest to pit bottom, decreases through time owing to erosional processes (Denny and Goodlett, 1956). Stone (1975), however, observed slopes of 13–30° in gravel-free soils on mounds estimated to be more than 250 years old. Nielsen (1963) found that mound slopes in silty soils were steeper (mean: 14°) than those in sandy soils (10°). Mound-crest to pit-center horizontal distance increases through time as the region of the pit nearest the mound infills with sediment from the mound, resulting in a progressive change of location for the deepest part of the pit.

LONGEVITY OF PIT/MOUND MICROTOPOGRAPHY

Age estimates for pit/mound microtopography are usually based upon one or more of the following lines of evidence: (1) relation to a known hurricane, tornado, volcanic eruption, or similar event (Held and Bryant, 1989); (2) inference based upon pit/mound morphology and soil development within pits (Denny and Goodlett, 1956; Lyford and MacLean, 1966); (3) dendrochonologic dating of trees growing on old mounds or downed boles (Zeide, 1981; Veneman et al., 1984); (4) dating increased growth in trees surrounding their uprooted neighbor(s) (Henry and Swan, 1974; Foster and Reiners, 1986); or (5) process measurement of pit infilling or root-plate breakdown (Small, 1987).

Estimates of pit/mound longevity vary greatly, and have been reviewed by Schaetzl and Follmer (1990). Due to the rapidity of mound erosion in the humid tropics, Putz (1983) was able to measure rates of pit infilling. In his study area, torrential rains on bare soil led to destruction of pit/mound microtopography within 5 to 10 years. Conversely, Schaetzl and Follmer (1990) studied sandy mounds in Michigan that were approximately 2400 years old, based on ^{14}C evidence. Most other ages ascribed to these features are 500 years or less (Oliver and Stephens, 1977; Swanson et al., 1982; Humphreys and Mitchell, 1983; Beatty and Stone, 1986). Radiocarbon dating methods were not used in early studies, despite the fact that mounds with buried organic material were reported (Goodlett, 1954; Denny and Goodlett, 1956; 1968; Shubayeva and Karpachevskiy, 1983; Beke and McKeague, 1984; Veneman et al., 1984). Age estimates of existing mounds do not imply maximum mound longevity per se, and therefore the possible lifespans of these features will greatly exceed 500 to 1000 years in many environments.

EFFECTS OF UPROOTING ON SOIL MORPHOLOGY

Uprooting disrupts soil horizonation, and retards and regresses soil development (Brown, 1977; Brown and Martel, 1981). Where O horizons are thick, however, as in the boreal forest, trees may be rooted mainly in the forest floor and subsequent uprooting may disrupt little or no mineral soil, leaving no net "negative signature" on soil development. Cremeans and Kalisz (1988) partially attribute the presence of Haplumbrepts and Hapludolls with thick, dark A horizons and lack of distinct eluvial horizons to frequent uprooting that enhances mixing of organic materials into the upper solum.

The amount of soil initially disturbed by uprooting is dependent on the architecture of major roots. Obviously, large trees disturb a greater surface area, perhaps to increased depths, than do small trees (Hall, 1988). Dying or dead trees tear up less soil than do healthy trees (Swanson et al., 1982), presumably because root rots in the former lead to increased root breakage during uprooting (Hubert, 1918). Cremeans and Kalisz (1988) found positive correlations between tree diameter at breast height (DBH) and area of soil disturbed, and calculated two regressions, for trees dead and trees living at the time of uprooting. Burns (1981) found that rooting depths increased as tree size increased up to 40 cm DBH, after which root systems did not appear to expand. Maximum root plate volumes encountered by Burns were about 4 m^3. Brewer and Merritt (1978) outlined how the area of soil disturbed could be calculated from two simple measurements made on pits and mounds. Mueller and Cline (1959) correlated rooting depth and root plate dimensions to soil wetness and DBH. They concluded that root plate size was primarily a function of DBH, but where root-restricting horizons were present the relationship was less clear.

Slump and erosion of sediment from the root plate are effective as a pedoturbation process, often producing irregular and discontinuous horizons within the treethrow mound (Pawluk and Dudas, 1982; Johnson et al., 1987), or leading to interfingering of horizons (Lutz and Griswold, 1939; Lutz, 1940; Hall, 1988). Slow root decay promotes slump and wash of sediment off the root plate; soil mixing is thus maximized and original horizonation is mostly lost. Rapid decay of binding roots, as occurs in many hardwoods (Beatty and Stone, 1986), allows the soil to fall off the plate as large clods, before surficial processes can break them apart and mix them. Thus, relatively large masses of the pre-uprooting soil may be observed within the mound core. The result of these bioturbations is increased pedon heterogeneity in the region of disturbance (Troedsson and Tamm, 1969; Troedsson and Lyford, 1973; Brown, 1977; Burns et al., 1983; 1984; Burns and Jordan, 1985; Hall, 1988).

In the slump process, soil horizons may fold over each other (Lutz and Griswold, 1939; Veneman et al., 1984; Beatty and Stone, 1986). Schaetzl (1986) attributed the formation of inverted soil profiles in mounds to uprooting on steep slopes with the tree falling downslope, thereby producing a root plate which "overhangs" from the vertical, and subsequent ground fire that burns the trunk and bracket roots and allows the root plate to fall onto the surface in an upside-down position (Schaetzl and Follmer, 1990). Although fire is not necessary for root plate overturning (Beatty and Stone, 1986), it does allow for more complete inversion and less overall soil mixing during mound formation, as it hastens the process substantially.

Rocks and large clasts are brought to the surface by uprooting (Lutz, 1960), and may later be buried by slump of soil from the root plate. In Wisconsin, uprooting had mixed sand and stones into silty upper sola over nearly 10% of the surface (Jacobson, 1969). Hole (1976) attributed stone concentrations in surface horizons of some soils to creep from upslope mounds (Daniels et al., 1987). Lutz (1940) found significantly more material larger than 1.0 mm diameter in mounds, which he

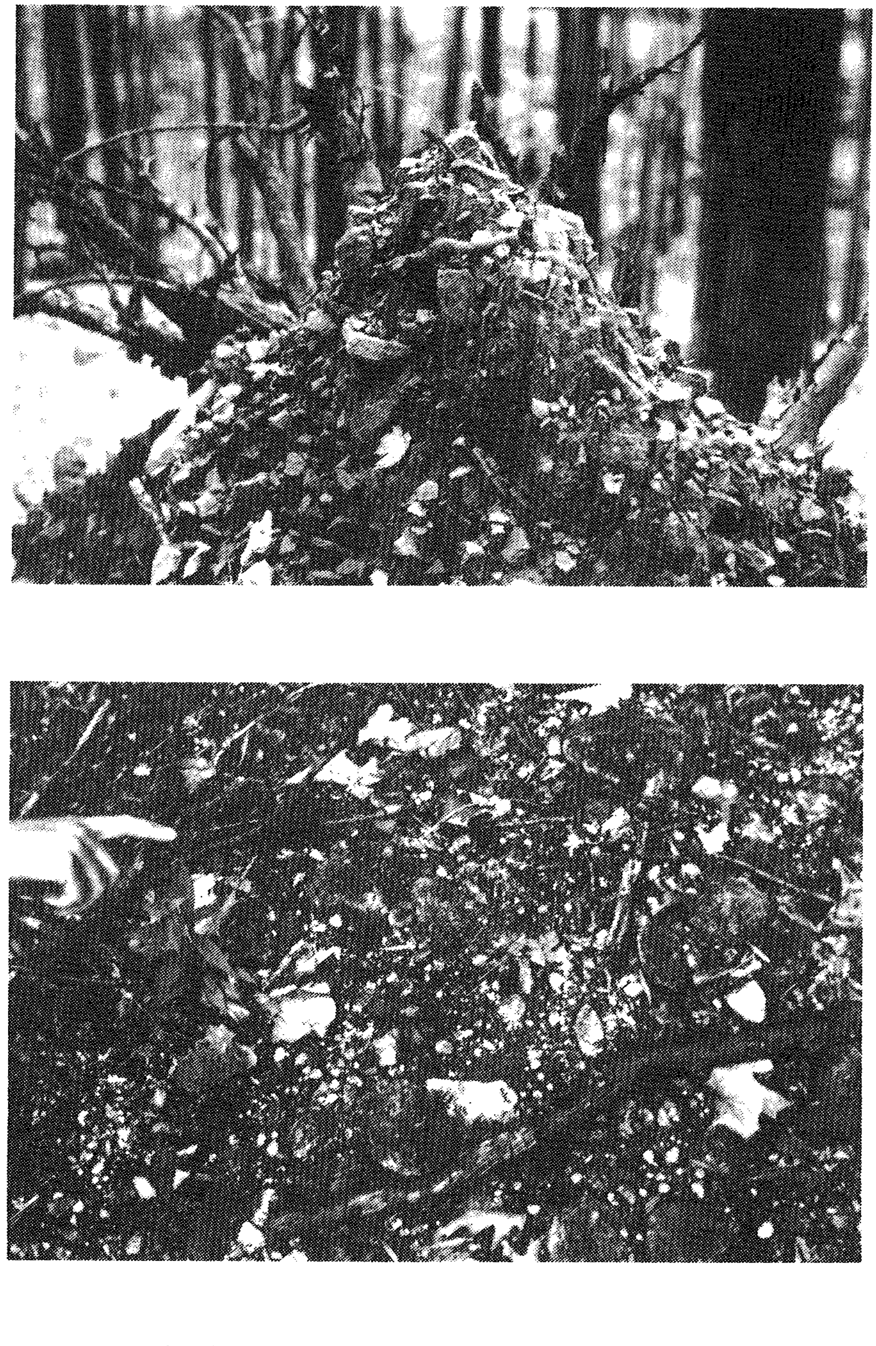

Fig. 1. (A): Root plate from shallow soils (Lithic Dystrochrepts) on sandstone bedrock, Potter County, Pennsylvania. Note the dense concentration of gravels on the soil surface. (B): Treethrow mound in the Kettle Moraine State Park, north unit, Wisconsin, showing dense mantle of gravels on the mound surface. Many gravels and cobbles are moss-covered and may be difficult to detect.

ascribed to upward mixing of ortstein (cemented spodic horizons) by uprooting. In this way, layers rich in archaeological artifacts may be mixed and/or buried by tree uprooting (Holmes, 1893; Wood and Johnson, 1978). Washing of fines off the root plate and/or mound may concentrate gravels and cobbles as an armor or lag (Denny and Goodlett, 1956; Nielsen, 1963; Small, 1987; Small et al., 1990; Fig. 1). Beatty and Stone (1986) discussed how such stones can provide evidence of uprooting, years after the mound itself has been obliterated (Lyford, 1964). Denny and Goodlett (1968) discussed how uprooting can form mounds of fine material surrounded by surface stone pavements, and vice versa.

Cross-sectional diagrams of mounds and pits illustrate their internal complexity (Goodlett, 1954; Armson and Fessenden, 1973; Brown, 1977; Schaetzl, 1986; Johnson et al., 1987; Hall, 1988). Most mounds are cored with B horizon material with interbedded, small clasts from the A or E horizon, due to the inherently thin nature of the latter horizons (Lutz, 1940; Lyford and MacLean, 1966; Troedsson and Lyford, 1973; Veneman et al., 1984). Some mounds, however, may consist of large blocks of C horizon material (Lutz and Griswold, 1939; Denny and Goodlett, 1956), suggestive of deep rooting (prior to uprooting) in soils with thin sola. In these mounds, B horizon material may slump off the root plate to flank the mound (Lutz and Griswold, 1939). In other soils, especially those with subsurface pans, the C horizon may remain undisturbed by uprooting (Hole and Schmude, 1959; Lyford and MacLean, 1966). Uprooting of shallowly rooted trees or those growing in wet, organic soils, may lead to mounds of predominantly A and O horizon material (Karpachevskiy et al., 1968). E horizons are seldom continuous across a pit-mound pair unless they post-date the uprooting event (Karpachevskiy et al., 1968). Therefore, they often terminate abruptly at the edge of the pit (Lutz and Griswold, 1939; Ives et al., 1972), but may be continuous beneath the mound (Schaetzl, 1986). The sides of mounds proximal to pits are primarily composed of lower B and C horizon material, whereas the distal side of the mound is often composed of upper solum material (Denny and Goodlett, 1956; Gaikawad and Hole, 1961).

EFFECTS OF MICROTOPOGRAPHY ON SOIL CHARACTERISTICS

Pits are sites of litter accumulation and often have overthickened O horizons (Nielsen, 1963; Armson and Fessenden, 1973; Federer, 1973; Shubayeva and Karpachevskiy, 1983; Beatty and Sholes, 1988; Hall, 1988; Table 1). Hart et al. (1962) reported mean litter accumulations over three years of: (1) 271 kg/ha on mounds; (2) 1012 kg/ha in pits; (3) 474 kg/ha on level sites. In their study area (New Hampshire), O horizon thicknesses were nearly four times greater in pits than on mounds, and were attributed to redistribution of litter after leaf fall. Lyford and MacLean (1966) found mean litter thicknesses of 12 cm in pits and 4.4 cm on mounds. In-washing of mineral soil from the root plate and mound can result in overthickened and possibly stratified A horizons in pits (Lutz, 1940; Hole and Schmude, 1959; Troedsson and Lyford, 1973; Pawluk and Dudas, 1982), or buried organic horizons (Shaler, 1890; Ives et al., 1972).

Snow depth, soil moisture content, and thickness of O, A, and E horizons are routinely greatest in pits and least on mounds, with undisturbed areas being intermediate with regard to these characteristics (Beatty and Stone, 1986; Beatty and Sholes, 1988; Schaetzl, 1990; Table 1). Compared to pit soils, mound soils experience greater temperature variability, owing to the low insulating abilities of thin litter and snow cover (Table 1). Pits are more temperature-buffered by thick litter and deep snow cover in winter (Kienholz, 1940; Federer, 1973; Beatty, 1984).

POST-UPROOTING PEDOGENESIS

Pit/mound microrelief affects pedologic processes primarily through spatial redistribution of litter and water inputs, and through differences in microclimate (Lag, 1951; Goodlett, 1954). In many regions, soil development is accelerated beneath pits more than beneath mounds. Strongly developed podzolic soils with thick E horizons, suggestive of concentrated leaching, are commonly found in pits beneath trees that produce acidic litter (Lutz, 1940; Lag, 1951; Burns et al., 1983, 1984). Denny and Goodlett (1956) noted that inter-mound soils in Pennsylvania had thin Podzol-like profiles while the mounds essentially lacked a soil profile. Goodlett (1954) explained the weak soil development in mounds by invoking frequent, near-surface freeze/thaw cycles, involving primarily needle ice. Veneman et al. (1984) found well developed Spodosols in pits and Inceptisols in mounds, and concluded that some summer precipitation, flowing laterally through O horizons into pits, concentrated water and organic acids in the pits (cf. Ives et al., 1972, p. 173). Schaetzl (1990) described treethrow pits, only slightly over 500 years old, with well-developed Spodosol profiles; adjacent mound soils had only incipient profile development. His data suggested that rates of post-uprooting pedogenesis were greatest in pits, lowest on mounds.

Burns (1981) suggested that many "egg-cup Podzols" in New Zealand may be relict treethrow pits rather than areas of enhanced leaching near tree boles as suggested by others. Ives et al. (1972) observed buried "egg-cup Podzols" where relatively unweathered material, brought to the surface by uprooting, had accumulated over more weathered soils. The buried soils always occurred in depressions ascribed to earlier uprooting; they suggested the term "windthrow Podzols" for such soils.

In contrast to the above studies, Bowers et al. (1986) observed pit/mound microtopography in Alaska where soil development was enhanced on mound sites. The relatively slow rate of pedogenesis in pits was ascribed to inhibition of vertical leaching by a high water table.

EFFECTS OF UPROOTING ON SOIL CLASSIFICATION

Certain pedogenic characteristics, such as the interrupted and cyclic horizon character of many Spodosols and Alfisols, imply past pedoturbation and may change their classification (Gaikawad and Hole, 1961; McKeague et al., 1969; Troedsson and Tamm, 1969; Miller et al., 1979; Lietzke and McGuire, 1987). Tongueing of E into B horizons may be due to infilling of former root channels (Lutz

Table 1. Comparison of Soil Composition and Characteristics Between Microtopographic Locations[a]

Characteristic of comparison	Mound	Level	Pit	Reference(s)
Soil development,	Low		High	4, 12, 13, 16
or profile differentiation	Low	High		5, 7
Winter temperature	Cool		Warm	6, 13
Spring temperature	Cool		Warm	1, 3, 6
Summer temperature	Warm		Cool	1, 3, 6
H_2O content	Low		High	1, 2, 3, 11, 13, 14
Saturated infiltration capacity	High	Low		7, 10
Pore volume	High	Low		10
Organic matter	Low		High	1, 2, 3, 13, 15
	High		Low	15
pH	High	Low		10
	Low		High	2, 14
Cation exchange capacity	Low		High	1
Available nitrogen	Low		High	1
Calcium	High		Low	15
	Low		High	1, 3
Magnesium	High		Low	15
Heavy mineral content	High	Low		10
Leaf litter accumulation	Low		High	2, 3, 8, 13, 15
0 horizon thickness	Thin		Thick	1, 7, 8, 11, 12, 13, 14, 16
A horizon thickness	Thin		Thick	1, 2, 3
Texture	Coarse	Fine		10
Frost action	High		Low	1, 5, 7, 8, 10, 13
Snow depth in mid-winter	Thin		Thick	1, 3, 6, 13
Snow depth at snowmelt	Thin		Thick	1, 13
Likelihood of being snowfree during the snowmelt period	High		Low	1, 13

[a]The adjectives "High," "Low," "Thick," "Thin," etc. indicate direction, not absolute magnitude, of variability. References: 1: Beatty, 1984; 2: Beatty and Sholes, 1988; 3: Beatty and Stone, 1986; 4: Burns, 1981; 5: Denny and Goodlett, 1956; 6: Federer, 1973; 7: Goodlett, 1954; 8: Hart, et al., 1962; 9: Kienholz, 1940; 10: Lutz, 1940; 11: Lyford and MacLean, 1966; 12: Moore, 1974; 13: Schaetzl, 1990; 14: Shubayeva and Karpachevskiy, 1983; 15: Stone, 1975; 16: Veneman, et al., 1984.

and Griswold, 1939; Pawluk and Dudas, 1982). Horizons such as E/B and B/E, common to many forest soils, may be a result of pedoturbation.

Uprooting may revert Spodosols to either Alfisols (Lutz, 1940), Inceptisols, or Entisols on mounds (Cutler, 1977; Schaetzl, 1990). In New Zealand, several authors noted that repeated uprooting maintains a landscape dominated by yellow-brown earth profiles (Inceptisols), whereas the presumed zonal soils of the region are Spodosols (Burns, 1981; Burns et al., 1983; 1984; Cutler, 1977). In Louisiana, uprooting reverts Paleudults to Hapludults on mounds (Burns and Jordan, 1985). Surprisingly though, Veneman et al. (1984) concluded that only 6% of the soils in their study area (Massachusetts) had been changed taxonomically by uprooting, despite the fact that 25% of the surface exhibited pit/mound topography.

GEOMORPHOLOGICAL ASPECTS OF UPROOTING

Recent studies have emphasized the importance of biogenic transport, including tree uprooting, in sediment budgeting. On steep slopes, uprooted trees generally fall downslope, producing a net downslope transport of sediment (Paton, 1978; Hall, 1988). Swanson et al. (1982) estimated that uprooting contributed 2% of the sediment transport in a watershed in Oregon (0.02 t/ha/yr, of which half was soil and half organics). Reid (1981) determined that uprooting produced 11.3% of the sediment yield from a basin in Washington (0.089 t/ha/yr). Data from New Zealand are an order of magnitude greater (0.4–1.3 t/ha/yr; Burns and Tonkin, 1987). Sediment transfer due to uprooting has been shown to be comparable to soil creep in some areas (Dietrich et al., 1982). Buttressing in tropical trees inhibits uprooting and, hence, slows sediment transfer processes attributable to uprooting in these environments (Herwitz, 1988).

Uprooting also plays an important role in sediment transfer via input to landslides and snow avalanches (Butler, 1987). Treethrow pits collect water and thus cause a reduction in soil shear strength, a natural triggering mechanism for debris avalanches and debris flows (Swanston, 1974). K.A. Bennett (pers. comm., 1982) observed that uprooting may trigger mass movement as vibrations during fall cause soil materials to reach their liquid limit and fail. Swanson et al. (1982) noted that debris avalanches may be initiated by uprooting, and that root plates can slide as far as 10 m downslope on steep slopes. Several authors have been able to calculate the amount of soil displaced by uprooting, and rates of downslope transport (Denny and Goodlett, 1956; Kotarba, 1970; Burns, 1981; Putz, 1983; Mills, 1984; Burns et al., 1984; Burns and Tonkin, 1987).

The above work has emphasized the importance of sediment transport via uprooting in certain environments. Denny and Goodlett (1956) concluded that uprooting in Potter County, Pennsylvania, produces a net downslope movement of material that may exceed all other slope processes combined. Burns and Tonkin (1987) estimated that sediment transport on forested slopes in New Zealand w three orders of magnitude greater than on nearby grassed slopes. Although the importance of uprooting as a mass wasting vector is clearly documented for some areas, extrapolation beyond the confines of a study area must be cautioned against. In light of recent evidence on the longevity of pit/mound microtopography, it seems that in many regions the rate of sediment transport by uprooting may have been exaggerated (Humphreys and Mitchell, 1983; Hall, 1988; Schaetzl and Follmer, 1990).

CONCLUSIONS AND FUTURE WORK

This paper summarizes part of the extensive and highly diverse literature concerning soil disturbance by tree uprooting. Soil horizonation is disrupted and soil development is temporarily arrested or even regressed by tree uprooting. Episodic disturbance by uprooting helps to explain the high spatial diversity found in forest soils at all scales of measurement. In most freely-draining situations, treethrow pits are sites of intense leaching, thick litter accumulations, and increased soil development, whereas mound soils show slower rates of pedogenesis. Thus the net overall effect of uprooting is to increase spatial variability in forest soils.

Much work remains to be done on the relationships between uprooting and sediment transport, preferably by examining slopes of varying steepness in different forest types. Root plate disintegration as a function of tree type (resinous vs non-resinous) and soil physical properties are research issues of merit. Related research topics include an analysis of root plate/soil mass ratios and how they vary for different tree species, environments, and soils. Only by improved measurement and wider areal study can we begin to amass the data required to assess accurately the importance of the uprooting process as a sediment transfer mechanism.

Aspects of pit/mound longevity have only recently been addressed. More work could be undertaken on this topic, since mounds often contain dateable organic materials. The great range in mound longevity, from less than 10 to more than 2400 years, suggests that factors and processes involved in their erosion or persistence might be examined and measured. Lastly, we suggest that future research on uprooting be performed at larger scales and over longer time periods.

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