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REDISTRIBUTION AND MIXING OF SOIL GRAVELS BY TREE UPROOTING*

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Gravel distributions within treethrow mounds and adjacent undisturbed soils in Wisconsin and Pennsylvania were examined to determine the pedoturbation effects of tree uprooting. Erosion of fine materials from the fresh root plate and subsequent treethrow mound leaves gravels as a lag deposit forming surface gravel armors. Continued slow erosion of remaining nongravelly materials diminishes topographic expression of the mound. In time, gravel armors remain as the only evidence of past uprooting events. **Key Words: treethrow, microtopography, gravel armor, pedoturbation.**

The uprooting of trees is a natural disturbance process that occurs in nearly all forested landscapes. Tree uprooting is an important geomorphic link between the atmosphere, biosphere, and pedosphere. Uprooting creates gaps in the forest canopy and microsite plant and soil variations on the forest floor that can influence forest species composition (Beatty and Stone 1986). Soil disturbance through uprooting can alter both the temporal and spatial progress of pedogenic processes. An uprooting event establishes a locus for soil erosion and sediment yield from forested landscapes, since only a portion of the disturbed soil pedon is returned to its place of origin through a combination of geologic, biologic, and atmospheric processes.

Evidence of past tree uprooting is common in many forested soils (Stephens 1956; Schaetzl et al. 1989a, 1989b). Uprooting often results in a mound, where soil slumps off the upturned roots (root plate), and an adjacent depression or pit that marks the former position of the roots (Fig. 1). The complexity of the resultant soil patterns within the mound depends in part on characteristics of the soil prior to uprooting as well as erosion and wasting processes after uprooting (Troedsson and Lyford 1973; Schaetzl et al. 1990). Soils in treethrow mounds often contain unmistakable evidence of their disturbance history, such as portions of inverted or overturned pedons (Schaetzl 1986), disturbed artifact layers (Holmes 1893; Wood and Johnson 1978), and buried organic materials (Denny and Goodlett 1956; Shubayeva and Karpachevskiy 1983; Beke and McKeague 1984; Veneman et al. 1984; Schaetzl and Follmer 1990). The deterioration and erosion of root plates result from the interaction of processes such as rainsplash, frost heave, soil creep, faunal activity, and root decay (Beatty and Stone 1986).

Concentrations of gravels on and within soils may provide a longer term record of pedoturbation events than many other pedologic characteristics (Johnson and Hester 1972; Johnson et al. 1987). Gravels are part of the skeletal framework of soils and are not easily translocated within the soil profile by horizonation processes, as are clays and silts. Gravels may be concentrated on the surfaces of treethrow mounds as a lag deposit or armor (Holmes 1893; Denny and Goodlett 1956, 1968; Nielsen 1963; Lyford 1964; Beatty and Stone 1986). Gravel armors can be effec-

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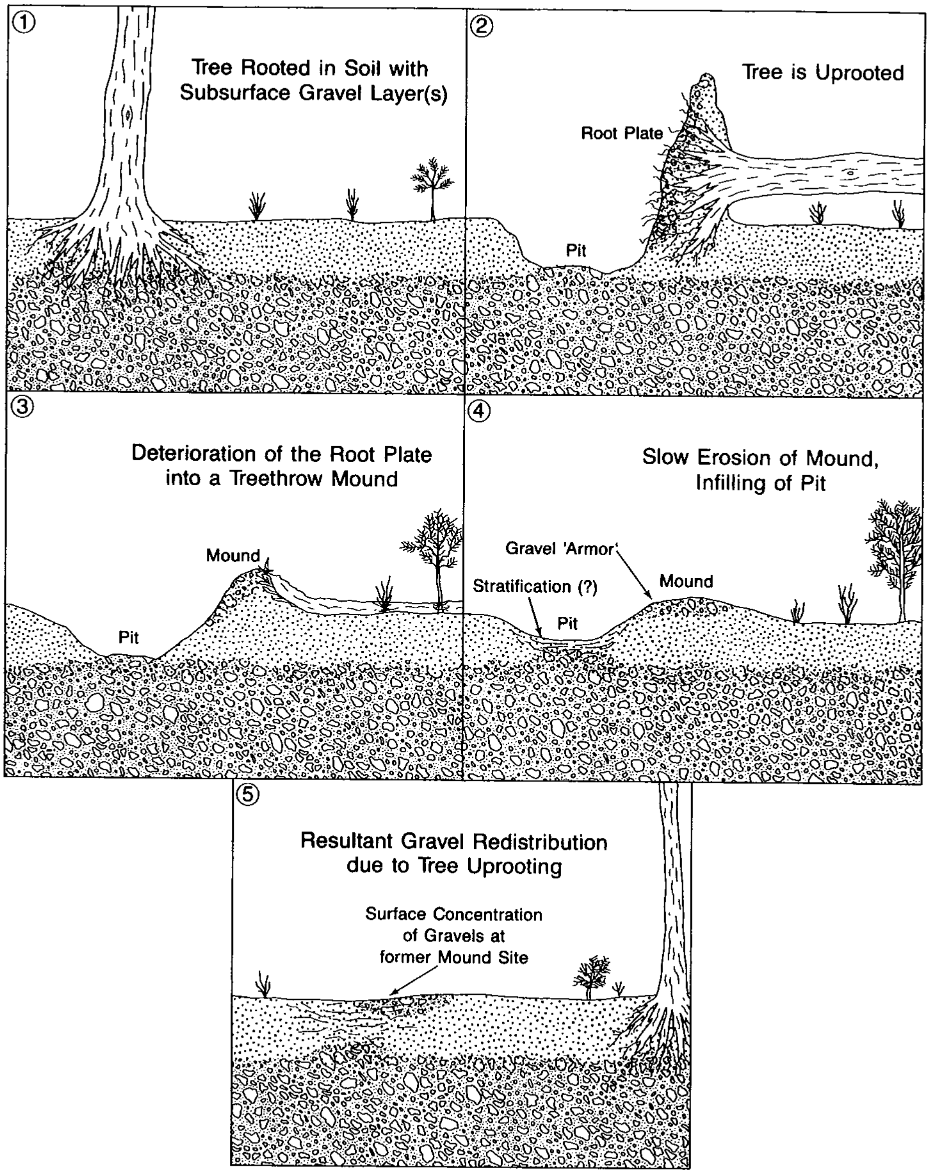

Figure 1. Diagrammatic representation of tree uprooting where a relatively gravel-free layer overlies a skeletal gravelly subsoil.

tive in slowing erosion of the treethrow mounds (Goder 1961).

Erosional processes will eventually eliminate any topographic expression of the mound, but gravel and coarse fragment concentrations can persist as indirect evidence of the uprooting event (Fig. 1). Both buried gravels (Holmes 1893) and

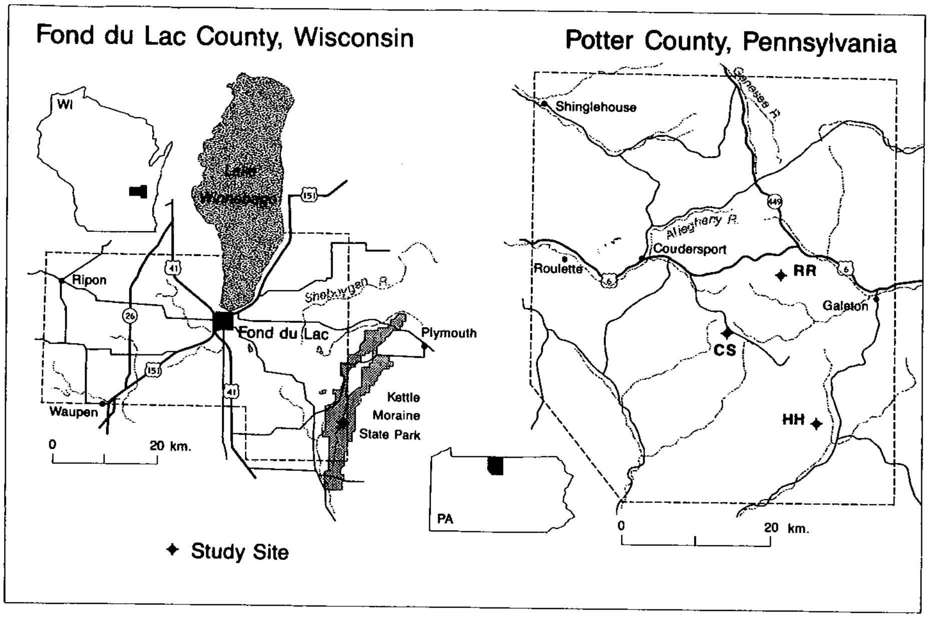

Figure 2. Location of the study areas in Wisconsin (WI1–WI3) and in Pennsylvania (RR1 and RR2, CS, and HH1 and HH2).

surface gravel armors (Beatty and Stone 1986) are possibly evidence of long past uprooting events. Denny and Goodlett (1968) suggested that surface gravel patterns in upstate New York, commonly interpreted as polygonal ground, may instead be related to processes of tree uprooting.

This study examined pedoturbation and erosion processes through an analysis of the redistribution of soil gravels (larger than 2 mm in diameter) by tree uprooting. Armors on treethrow mounds have been previously described qualitatively. This study compared quantitatively the gravel distributions by depth in treethrow mounds with corresponding data from adjacent soils that had not experienced recent uprooting ("undisturbed" pedons). Our objectives were to determine whether gravels were indeed concentrated as lag deposits on mound surfaces, and to elucidate how the gravel distributions produced by uprooting were affected by the gravel stratification prior to uprooting (using the adjacent undisturbed pedon as a surrogate). These research questions were investigated in two regions of contrasting soils. In the first region, rounded gravels occurred in otherwise sandy soils. In the second region, flat, plate-like gravels occurred upon and within loamy soils. In both regions, mounds used for this study were presumed to be old landscape features (estimated age greater than 200 years) created by old growth forest species perhaps different from those that presently exist in the study regions. These mounds contained little or no woody remnants of the trees responsible for their formation. Both study regions had experienced frost processes, so we could make inferences regarding the periglacial or pedoturbation origin of the gravels.

Study Areas

The two forested study areas exhibit pronounced mound and pit topography likely due to tree uprooting. The first area is within the Kettle Moraine State Forest

Figure 3. Rainsplash pedestals of soil material capped by sandstone fragments, on a root plate in Potter County, PA. Numbered tags identify pins on mound erosion study sites (Small 1987).

in Fond du Lac County, southeastern Wisconsin (Fig. 2). Kettle Moraine is a Woodfordian, interlobate moraine (Black 1969). This constructional, ice-contact landscape has numerous short but steep slopes (angles greater than 20°). The Rodman soils (sandy-skeletal, mixed, mesic, Typic Hapludolls) are formed in surficial materials that are predominantly glaciofluvial sands containing abundant, well-rounded dolomitic gravels and cobbles (Link 1973; Hole 1976). Treethrow mounds at the site are often small and covered with sparse moss or grassy vegetation; commonly about half of the surface area of a typical mound is covered with gravels.

The second study area is in the Susquehannock State Forest in central Potter County, Pennsylvania, on the high, dissected Allegheny Plateau (Fig. 2). The site lies approximately 20 km south of the Wisconsinan glacial boundary (Berg 1980), and has likely been affected by periglacial processes (Denny and Goodlett 1956; W. J. Waltman, personal communication). Narrow flat-topped divides occur at the head of numerous, sometimes very steep slopes (angles greater than 30°) that lead into canyon-like valley floors. Surficial materials at this site are principally residuum from Paleozoic sandstones and shales, which weather into plate-like (flaggy) clasts thinner than 1 cm. DeKalb soils (loamy-skeletal, mixed, mesic, Typic Dystochrepts) are less than 60 cm thick on upper slope convexities in sandstone and shale residuum. Lackawanna soils (coarse-loamy, mixed, mesic, Typic Fragiochrepts) on ridge crests are more than 80 cm thick and have formed in frost-worked deposits (Goodman et al. 1958). A fragipan often overlies a flaggy, almost impenetrable frost-affected substrate in the Lackawanna soils. Because of the plate-like shapes of the weathered rock fragments, many young mounds and root plates exhibit pedestals (described as rainsplash pillars by Bishop et al. 1980) with small sandstone clasts acting as a caprock above finer material (Fig. 3). Significant

TABLE 1

SOILS, SEDIMENTOLOGIC, AND GEOMORPHIC COMPARISON OF THE TWO STUDY AREAS

Parameter	Pennyslvania	Wisconsin
Type of landscape (primarily)	erosional	constructional
Age of landscape (years)	>2,000,000	11,000-13,000
Predominant gravel shape	plate-like	spherical
Texture of fine fraction	loamy	sandy
Approximate percent of surface covered with forest litter in midsummer	100%	60%
Mean dimensions (cm) of treethrow mounds sampled		
width	264	169
length	413	244
height above ground surface	46	17
height above pit bottom	52	24
Mean mound volume[a] (m^3)	2.63	0.37

[a]Modified from Mills (1984).

faunal activity or influence was not detected upon or within our study mounds. Continuous litter layers up to 2 cm thick cover most of the mound surfaces (Table 1).

Materials And Methods

Soil samples were collected from paired mound and neighboring undisturbed pedons. Three mound/undisturbed pairs were sampled in Wisconsin (WI1-WI3) at 43°35′35″N, 88°11′49″W. Five mound/undisturbed pairs were sampled in Pennsylvania at sites along Hungry Hollow Road (HH1 and HH2; both at 41°35′33″N, 77°43′25″W), along Ridge Road (RR1 and RR2; both at 41°44′58″N, 77°47′23″W), and on State Route 44 near the Cherry Springs airport (CS; 41°42′11″N, 77°53′36″W).

Bulk soil samples of 10-15 kg were removed from a 30 cm by 30 cm square on the surface of mounds and undisturbed sites. Layers of soil three to 10 cm in thickness within the square were removed one at a time and collected for subsequent analysis. Excavation in the 30 cm square vertical column of soil continued to depths of 30-50 cm, which is deeper than the thickness of most mounds. Laboratory analysis consisted of air drying, sieving, and weighing each of the sieved fractions. Sieve diameters used were 2, 2.35, 3.35, 4.75, 8, 16, 32, and 63 or 76.2 mm. Gravel percentages, by weight for each sieve size, were plotted by depth at the midpoints of sampled intervals. Sand, silt, and clay percentages for selected sites were determined by the hydrometer method (Gee and Bander 1986).

Results

The sampled treethrow mounds in Potter County, PA, are more than seven times larger by volume than those in the Wisconsin study area (Table 1). The larger size is probably due to larger root plates in the former area, rather than mound age, likely attributable to different mound-forming tree species in the two study areas.

The Wisconsin study soils have well-rounded, dolomitic gravels throughout the solum (Table 1). Gravel content changes little with depth in the undisturbed pedon at site WI1 (Fig. 4), and gravel percentages exceed 60% by weight at this site. Two of three undisturbed Rodman soils (WI2 and WI3) have a sandy, relatively gravel-free layer of moderate thickness (5-10 cm) at the surface (Fig. 5 and 6). Uprooting in these soils typifies pedoturbation in crudely stratified materials, with a fine layer overlying a coarse, gravelly zone.

Surface concentrations of gravels in the

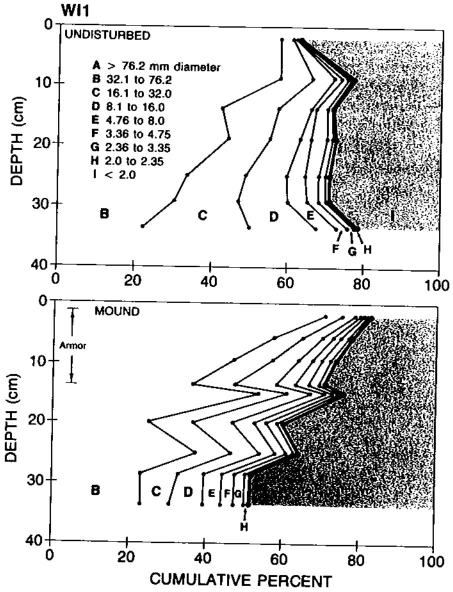

Figure 4. Particle size distribution (for both gravels and fines) with depth within the WI1 mound and undisturbed soils.

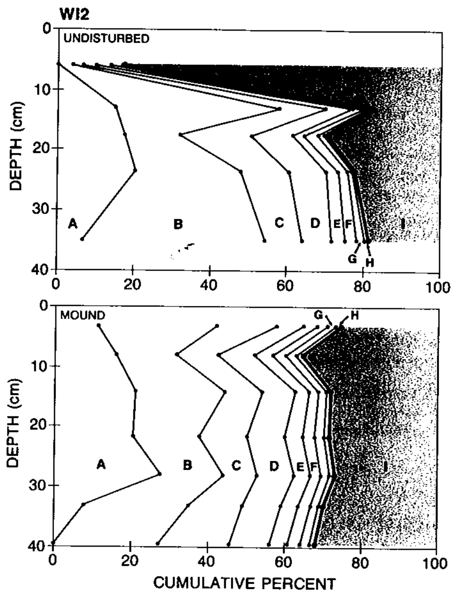

Figure 5. Particle size distribution with depth within the WI2 mound and undisturbed soils.

three Wisconsin mounds are greater than those found in the undisturbed soils (Fig. 4 to 6). The difference is especially noteworthy at site WI1, where a distinct gravel armor is present in the upper 13 cm of the mound (Fig. 4). At sites WI2 and WI3, the proportions of the largest gravels near the surface of the mounds are substantially greater than in the respective undisturbed pedons. Most mounds in Rodman soils have a nearly continuous, surficial armor of gravel, one gravel layer in thickness—the latter morphologic feature was not necessarily revealed by the data. These findings demonstrate that uprooting can result in the formation of surface armors in soils that have either relatively gravel-free zones at the surface or uniform distributions of gravels with depth.

Both undisturbed soils at the Ridge Road sites in Pennsylvania (Fig. 7 and 8) show generally uniform distributions of gravels with depth, similar to that in the undisturbed Rodman soil at WI1, but have considerably less gravel (about 50% through the pedon) than at the WI1 site. Surface armor is not evident in the mounds at Ridge Road. The distribution of gravels in the undisturbed sites is nearly invariant with depth and has been only slightly altered by uprooting. These soils exemplify the homogenized character of soils that we have often observed within treethrow mounds.

Sites CS, HH1, and HH2 are in DeKalb soils, which are comparable in gravel content to Rodman soils. Textural trends for the Cherry Springs undisturbed site (Fig. 9) are similar to those at WI1, RR1, and RR2, with a nearly uniform distribution of gravels with depth. Pedoturbation and subsequent processes, however, have resulted in a gravelly lag concentrate on the CS mound that is conspicuously dominated by gravels larger than 63 mm in diameter. Upward concentration of these large gravels from the subsoil to the sur-

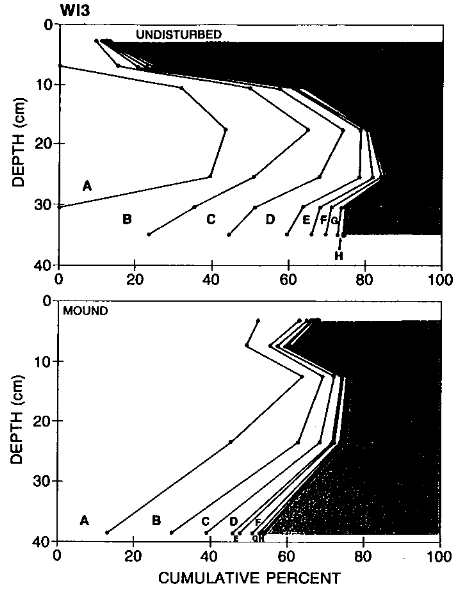

Figure 6. Particle size distribution with depth within the WI3 mound and undisturbed soils.

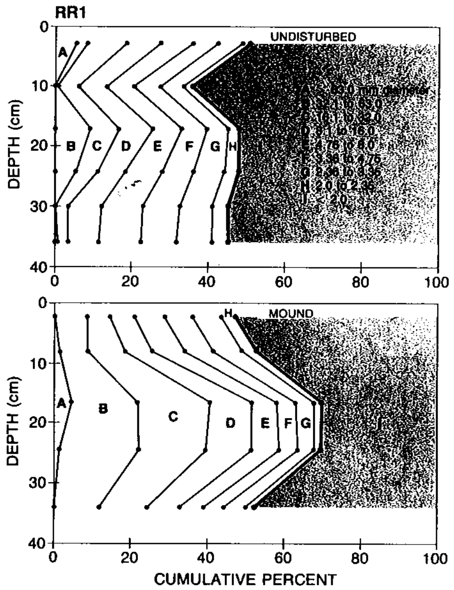

Figure 7. Particle size distribution with depth within the RR1 mound and undisturbed soils.

face of the mound is a notable effect of tree uprooting in the CS soil.

Textural patterns for the mound and undisturbed sites at HH1 and HH2 were essentially identical. Examination of the HH2 mound and undisturbed pair (Fig. 10) reveals that, unlike the other examples, the undisturbed pedon has a thick gravel armor at the surface. Here, instead of aiding in the formation of an armor, pedoturbation has homogenized the soil and destroyed a preexisting surface armor.

Discussion

This research documents the existence of gravel armors on treethrow mounds. Such armors have important implications for soil erosion and slope stability (Goder 1961). Trees on slopes generally fall downslope upon uprooting, and treethrow is therefore often viewed as a dominant process of downslope transfer of regolith (Denny and Goodlett 1956; Dietrich et al. 1982; Swanson et al. 1982), although Schaetzl and Follmer (1990) recently questioned this assertion. Whether tree uprooting leads to the production of a surface armor on soils that previously had gravel-free layers at the surface, or whether it destroys preexisting armors, the effect on long-term rates of sediment transfer can be important. This research documents that both of the above scenarios occur.

The morphology of the mound armors is not unlike that of desert hamadas, stone pavements, or erosion pavements (Lowdermilk and Sundling 1950; Sharon 1962, figure 2; Cooke and Warren 1973), which are lag deposits formed by water and to a lesser extent wind erosion of fines from sediments containing both fine and coarse fragments. Unlike desert environments, however, fine material in the humid environment mound soils does not develop a crust that markedly inhibits erosion (Sharon 1962; Cooke 1970). Also, the forest soils do not have vesicular, nearly stone-free layers immediately beneath the

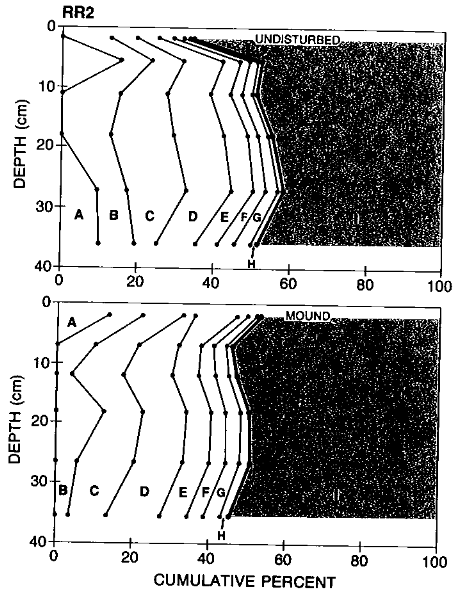

Figure 8. Particle size distribution with depth within the RR2 mound and undisturbed soils.

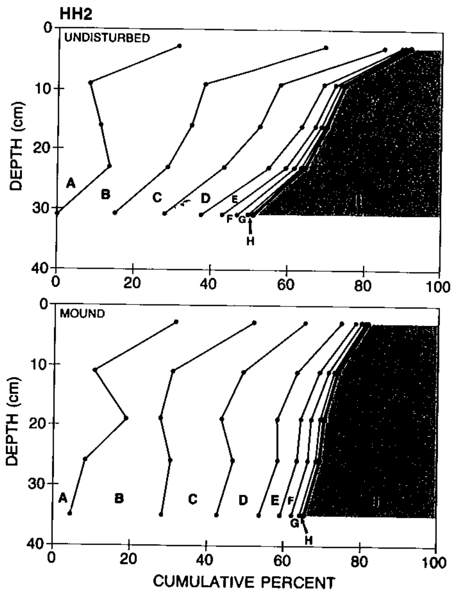

Figure 10. Particle size distribution with depth within the HH2 mound and undisturbed soils.

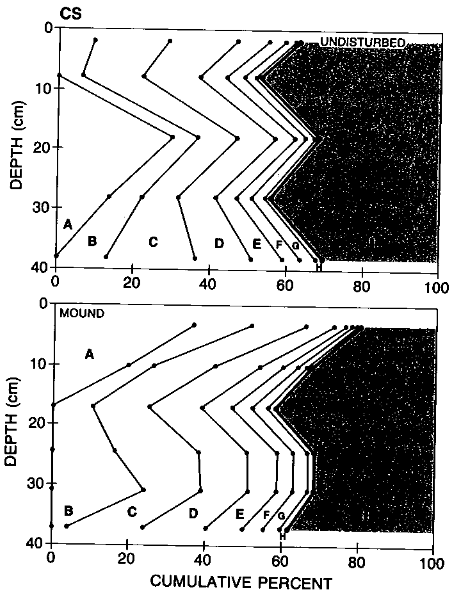

Figure 9. Particle size distribution with depth within the CS mound and undisturbed soils.

surface armor, as do many soils beneath desert pavements (Springer 1958; Cooke 1970). An additional difference between desert pavements and these armors on forest soils is the degree of vegetative cover on the surface. Desert pavement often lacks vegetative cover (Cooke 1970), whereas the armors in this study formed under forest cover. Lowdermilk and Sundling (1950) restricted the use of "desert pavement" to erosional lag deposits formed in arid climates; they preferred the term "erosion pavement" for gravel armors in humid regions that form when vegetative cover is removed from a soil. Disturbance of preexisting vegetation by uprooting should therefore be viewed as an important, initiating factor in the formation of gravel armors on mounds.

Lack of nearly gravel-free layers immediately below the surface armors negates the possibility that upward translocation by freeze and thaw activity is the primary cause of the mound armors (Springer 1958; Inglis 1965; Cooke 1970).

TABLE 2
SOIL TEXTURES (EXCLUDING GRAVELS) FROM TWO PENNSYLVANIA MOUND/UNDISTURBED PAIRS

Site	Depth cm	% Sand (2000–50 μm)	% Silt (50–2 μm)	% Clay (<2 μm)	Textural class
RR1—undisturbed	0–6	45.8	42.0	12.2	loam
	6–14	43.7	43.2	13.1	loam
	14–20	45.9	40.1	14.0	loam
	20–28	44.8	39.0	16.2	loam
	28–32	45.7	38.3	16.0	loam
	32–40	45.3	37.5	17.2	loam
RR1—mound	0–4	35.8	40.2	24.0	loam
	4–12	34.7	36.3	29.0	clay loam
	12–21	31.8	40.1	28.1	clay loam
	21–28	35.7	36.2	28.1	clay loam
	28–40	33.9	36.1	30.0	clay loam
HH1—undisturbed	0–6	54.5	34.3	11.2	sandy loam
	6–16	56.5	30.5	13.0	sandy loam
	16–24	53.5	33.3	13.2	sandy loam
	24–32	52.8	33.0	14.2	sandy loam
	32–42	55.5	28.3	16.2	sandy loam
HH1—mound	0–3	34.9	42.1	23.0	loam
	3–9	34.8	41.2	24.0	loam
	9–18	36.8	39.2	24.0	loam
	18–23	40.8	37.2	22.0	loam
	23–27	40.9	37.0	22.1	loam
	27–34	46.5	34.5	19.0	loam
	34–40	49.5	33.5	17.0	loam
	40–46	48.8	33.1	18.1	loam

The low clay contents (Table 2) and lack of desiccation cracks in the soils at the time of sampling further suggest that shrink and swell activity is an unlikely cause of the surface armors (Mabbutt 1965; Johnson and Hester 1972).

The formation of the gravel armors on treethrow mound sites probably results from two similar, yet often spatially and temporally disjunct, suites of processes. Initially, concentration of gravels begins during root plate deterioration. The largest gravel clasts are often retained within the root plate for as long as it persists, while fine materials are preferentially washed away (Lutz 1960; Denny and Goodlett 1968). These processes may be especially pronounced in the Rodman soils, where the nongravel materials are sandy and thus easily entrained and washed from the root plate. Soil materials in the root plate, now gravel-enriched, are deposited as the last (uppermost) layers of the treethrow mound (Fig. 4 and 9).

The second and perhaps most important suite of armoring processes involves erosion and lowering of the mound surface over a timespan that may take 2000 or more years in some regions (Schaetzl 1986; Schaetzl and Follmer 1990). Patches of bare soil on mounds, observed at the Wisconsin sites (Table 1), suggest the current operation of surface wash processes in this landscape (Lowdermilk and Sundling 1950). Pedestals (Fig. 3) also point to erosion by water, whether by rainsplash or sheetwash (Bishop et al. 1980). The thin (generally less than 5–10 cm) yet nearly contiguous nature of most armors on mound remnants also suggests that they owe their character more to processes that remove fine materials but leave the gravels behind as a lag, than to direct deposition of exceedingly gravelly materials on the mound surface.

The Lackawanna soils in the mounds at Ridge Road have loam and clay loam textures (excluding gravels) throughout the profile (Table 2) and lack gravel armors (Fig. 7 and 8). Perhaps the higher clay content here, in comparison to the sandy Wisconsin soils, inhibits processes that would wash away the fine materials and leave the gravels behind as a lag deposit. Gravels are not easily eroded by surface wash, and many clays remain behind because they too are not as easily entrained as are sand and silt particles. The increased clay and decreased sand content of the RR1 mound, in comparison to the undisturbed pedon (Table 1), suggests that some wash may be occurring but that the more easily entrained sand grains are the primary size fraction that is affected.

The concentrations of gravels near the surfaces of the mounds will not likely decrease with time, since additions of relatively gravel-free colluvium from upslope are unlikely to accumulate on these topographic highs. Continued erosion will more likely wash additional fine materials from the mounds, thereby further concentrating the gravels. Overland flow in these forests is seldom, if ever, rapid enough to entrain and transport the gravels off the mound tops. Presumably, erosion will continue on mounds as long as bare soil is exposed and unprotected by gravels or thick leaf litter. The rate of erosion may slow with time, however, as the topographic expression of the mound is reduced and as the lag deposit thickens and becomes more spatially contiguous (Lowdermilk and Sundling 1950; Goder 1961; Sharon 1962). Old, eroded, low mounds should have more pronounced lag armors than young, large mounds, within which the gravels would still be randomly distributed, other factors being equal.

Mound height above the undisturbed forest floor, mound length, and mound width data not reported here show that the Hungry Hollow (HH) mounds are the largest of all mounds sampled. Armors are absent or weak at best on the HH mounds (Fig. 10), and particle size distributions do not indicate preferential erosion of sands from the uppermost mound layers (Table 2). The generally small mounds with sandy soils in the Wisconsin study area, conversely, have distinct armors. Topographic expression of the mound may eventually disappear, but a gravel armor will persist as evidence of the uprooting event (Fig. 1; Denny and Goodlett 1968). Complete eradication of the HH mound microtopography and erosion of most of the fine materials contained within the mounds would be sufficient to concentrate gravel fragments at the surface to the degree observed in the undisturbed pedons nearby.

The mounds in this study all showed evidence of organic enrichment in the upper 5–10 cm of the sampled profile. The presence of an A horizon implies a general stability of the mound surface, or perhaps very slow erosion (Mabbutt 1965, 137) as well as moderate age. The gravel armor, therefore, likely contributes to mound stability, inhibits erosion, and prolongs mound longevity.

Over long time periods, the entire forest floor should eventually undergo disturbance through the tree uprooting process (cf. Brewer and Merritt 1978), and eventually all undisturbed pedons in these two areas could be armored to greater or lesser degrees. Tree uprooting is therefore a process that produces armors in gravelly soils regardless of original stratification. Tree uprooting may temporarily destroy preexisting surface armors and gravel stratification, but erosion of the mound will lead to the later reappearance of the armor (lag deposit).

Conclusions

Unlike most horizonation (Buol et al. 1989) or homogenization (Johnson et al. 1987) processes, tree uprooting acts more or less indiscriminantly on both the fine and coarse fractions of soils (Lutz 1960). Tree uprooting, therefore, often functions initially to homogenize gravel distributions within soils, whether the predisturbance soil has a fine layer overlying a gravelly zone (as at sites WI2 and WI3), a maximum of gravels near the surface (sites HH1 and HH2), or a relatively uniform distribution of coarse materials with depth (sites CS, RR1, and RR2). We infer that mound armors are formed as a relatively gravel-rich layer of sediment is deposited on the mound during the final stages of root plate deterioration, and subsequent sheetwash and rainsplash erosion removes still more fine materials from the mound, leaving gravels behind as a lag concentrate. The shape of gravels does not appear to have an impact on armor formation. Eventually, topographic expression of a mound will become undetectable, but a surface gravel concentration (interpreted as an armor on an undisturbed site, as at Hungry Hollow) will indicate its former location.

Previous research on gravel armors and erosion pavements focused either on arid climates and/or sites devoid of vegetative cover (e.g., disturbed areas, periglacial regions). This research documents the formation of soil armors in humid, forested landscapes. These armors can form quickly if the fine materials are sandy and thus easily winnowed and washed away. Where the fine materials are not easily entrained, nearly complete erosion of the mound may be required before an armor is formed. Further, our direct comparison of soils pedoturbated by tree uprooting with undisturbed pedons supports the hypothesis advanced by Denny and Goodlett (1968) that discrete, spatially disjunct concentrations of surface soil gravels in areas previously strongly affected by periglacial frost processes are much younger than the Pleistocene and are attributable to late Holocene floral pedoturbation rather than to frost processes.

Gravel armors have notable implications for significantly enhancing mound and pit longevity while reducing soil erosion and sediment yield from forested landscapes, and thus increasing long-term slope stability. Although gravel armors are the result of short-term, accelerated erosion of fine materials, over long timespans the gravel armor will serve to inhibit soil erosion. Therefore, our findings suggest that uprooting in gravelly soils, normally viewed as a major mechanism of downslope sediment transport, may indeed be more important as a means by which, ultimately, land surface stability is maintained and soil erosion is controlled in forested landscapes.

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