# Tree uprooting: review of terminology, process, and environmental implications

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Floralturbation, the mixing of soil by the action of plants, is an important pedologic process in forested areas. The uprooting of trees, the most obvious form of floralturbation, is a natural process found in nearly all forested landscapes. The term uprooting is distinct from such terms as treethrow, treefall, and blowdown, which imply processes that may occur without soil disturbance, as in bole snap. Uprooting is exacerbated by shallow rooting, topographic exposure, weakened condition of the tree, certain cutting practices, and (or) low soil cohesion and shear strength. The root plate of an uprooted tree may deteriorate into a pit-mound pair, the size and shape of which depends on the characteristics of the root plate and the amount of backward displacement during uprooting. This paper (*i*) provides a synthesis of related terminology on the topics of treefall and uprooting, (*ii*) examines various lines of evidence for the widespread occurrence of uprooting, (*iii*) summarizes disturbance cycles for catastrophic uprooting events in different environments, (*iv*) discusses several examples of the economic import and scale of widespread uprooting events, and (*v*) reviews environmental factors and silvicultural practices that may lead to increased uprooting or can be used to minimize its likelihood.

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La « floralturbation », qui est le mélange du sol sous l'action des plantes, est un processus pédologique important dans les surfaces boisées. Le déracinement des arbres, la forme la plus évidente de floralturbation, est un processus naturel qu'on rencontre dans presque tous les paysages forestiers. Le terme déracinement se distingue des termes soulèvement, chute d'arbre et renversement, qui n'impliquent pas de perturbation du sol, comme lorsqu'un arbre se casse. Le déracinement est accentué par un enracinement superficiel, une exposition due à la physiographie, une faiblesse de l'arbre, certains procédés d'exploitation et (ou) une faible cohésion du sol et une déformation de cisaillement. Le système racinaire d'un arbre déraciné peut se transformer en une paire de butte–dépression dont la dimension et la forme vont dépendre des caractéristiques du système racinaire ainsi que du déplacement rétrograde durant le déracinement. Cet article (*i*) donne une synthèse de la terminologie pertinente concernant la chute et le déracinement des arbres, (*ii*) montre certains faits d'évidence portant sur l'ampleur du phénomène de déracinement, (*iii*) résume le cycle des perturbations reliées à des déracinements catastrophiques dans divers milieux, (*iv*) donne des exemples concernant l'étendue et l'importance économique des déracinements et (*v*) passe en revue les facteurs environnementaux et les pratiques sylvicoles pouvant mener à l'augmentation des déracinements ou pouvant être employés pour minimiser leurs éventualités.

[Traduit par la revue]

## Introduction

Approximately one-third of the earth's land surface is covered by forest (Leith 1975). The uprooting of trees, observable in nearly all forested areas, provides an important process link between the biosphere, pedosphere, and atmosphere. Uprooting has been reported in various publications for centuries. Early, brief reviews on the topic (Hubert 1918; Lutz and Griswold 1939; Lutz 1940; Lyford and MacLean 1966), however, were either not international in scope or very focussed topically. This review, in conjunction with others (Schaetzl *et al.* 1989), provides an extensive modern synopsis of investigations into the significance and implications of the uprooting process. Our purpose is to bring together a growing body of international literature on this topic and to synthesize general truths about the uprooting process.

### *Definitions and examples of uprooting*

Floralturbation (or floralpedoturbation) is the mixing of soil by the action of plants (Hole 1961; Johnson *et al.* 1987). In general, there are five mechanisms by which plants disturb and (or) mix the soil: (*i*) root expansion during growth; (*ii*) decay and infilling of former root channels; (*iii*) settling of the soil due to water extraction by roots; (*iv*) agitation of the plant during storms, which promotes root move-

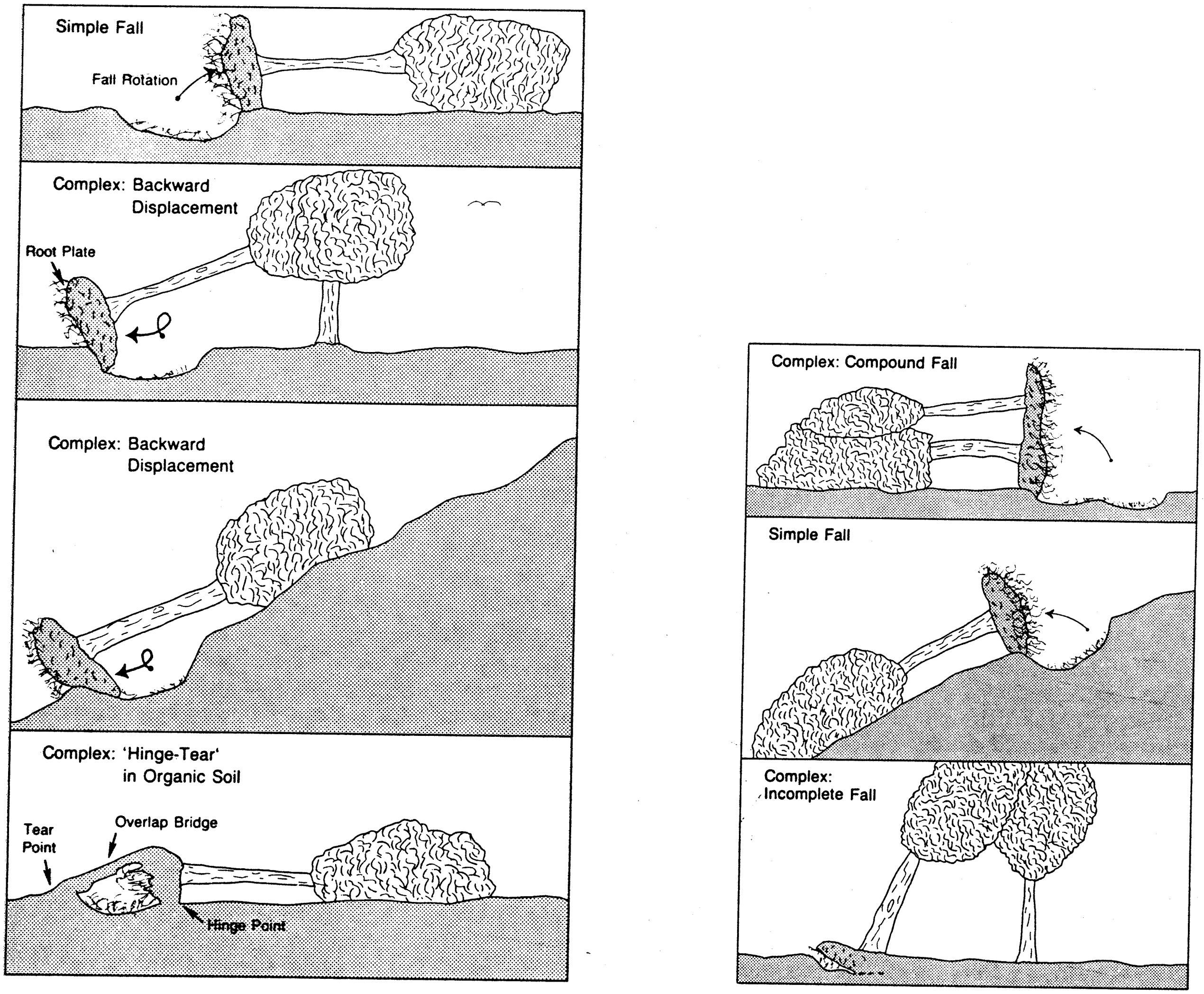

FIG. 1. Diagrammatic, not comprehensive, representation of examples of uprooting, both simple and complex.

ment; and (*v*) uprooting. (See also Moore 1933; Lutz and Griswold 1939; Roberts 1961; Butuzova 1962; Retzer 1963; Armson and Fessenden 1973; Stone 1977; Paton 1978; and Ryan and McGarity 1983.)

Uprooting is the most obvious type of floralturbation in forested areas. The term *uprooting* implies that a tree has fallen with most of its larger roots intact, *tearing up* soil in the process (Fig. 1). Brewer and Merritt (1978) reported an average of 11.9 $m^2$ of soil surface disturbed at the base of uprooted mature-type trees; Putz (1983) found a mean disturbance area of 16 $m^2$. Likewise, the upper metre or more of soil may be disrupted by uprooting. Several researchers equate the term *arboturbation* to uprooting (Brown 1979; Wang and McKeague 1986; Beke and McKeague 1984); Swanson *et al.* (1982) used the term *root throw*. Terms such as *treefall* or *tree tip*, though often equated with the term *uprooting*, may also refer to trees whose trunks have snapped near the base with little or no soil disruption.

A forcing mechanism for uprooting is not implied in these terms. Root throw (Swanson *et al.* 1982) and treethrow (Denny and Goodlett 1968) are generic terms that do not mention forcing mechanisms. Common synonyms such as *windthrow, windfall, blowdown, windbreak*, and *windblow* require wind as a forcing agent. Strong winds may be of meteorological origin (tornadoes, hurricanes, downbursts, chinooks, katabatic winds), or may result from volcanic activity, avalanches, forest fires, or extraterrestrial phenomena (meteorite impact). Overloading by snow and ice on crowns (*snow-throw, snow-down*), however, is often sufficient to topple trees, especially conifers (Hubert 1918; Stephens 1956; Rozmakhov *et al.* 1963; Beatty and Stone 1986). Slow, downward snow creep may also uproot small trees (In der Gand 1968). Stephens (1956) called the forces of wind, snow, and ice *mechanical factors* of uprooting. Old trees may even topple under their own weight, as roots die and decay (Bormann and Likens 1979*a*, 1979*b*). Many trees are uprooted by the *domino effect*, rather than directly by wind or snow overload (Brewer and Merritt 1978). Gratkowski (1956) found that the proportion of trees knocked down in this manner can approach one in four. Stephens' (1956) *physiological factors* of uprooting included shallow rooting, death and decay of roots, and weakening of roots by disease, pathogens, fire, or senescence (Cline and Spurr 1942; Day 1950; Gratkowski 1956; Stephens 1956; Fraser 1962; Pyatt 1966; White 1979; Beatty and Stone 1986).

Uprooting occurs when lateral forces applied to the tree overcome the root anchorage (Day 1950; Putz *et al.* 1983). When stem strength is great, soil to root adhesion becomes the weak link in the system and uprooting occurs. Soil provides support in two ways: (*i*) by cohesive forces in silts

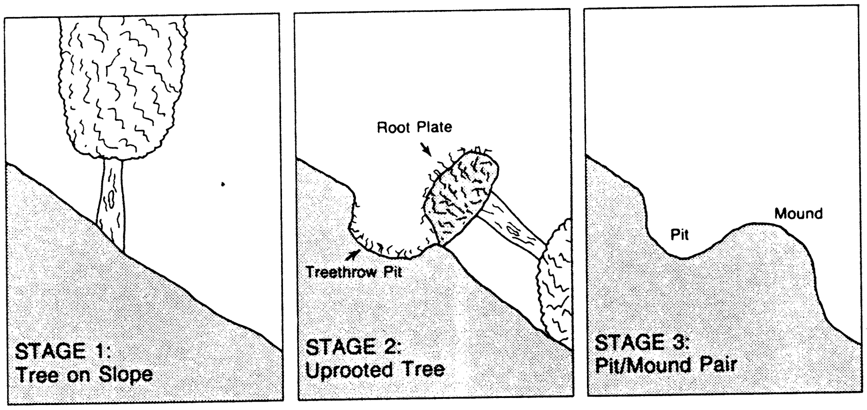

FIG. 2. Diagrammatic representation of the process of uprooting and soil slump from the root plate, resulting in a pit–mound pair.

and clays, and (*ii*) by frictional forces and shear strength in coarser-textured soils (Trousdell *et al.* 1965). Wetness and saturation greatly reduce soil cohesion and shear strength, thereby increasing the possibility of uprooting versus snap (Lutz 1960; Pyatt 1966). Conversely, when root strength and anchorage exceed stem strength, snap or breakage of the bole without uprooting may result.

Factors that influence whether a tree uproots or snaps are the root system, wind speed and direction, soil depth and water content, crown size and shape, trunk strength, height, and whether it is struck by falling trees (Baker 1915; Boe 1965). Naka (1982) suggested that bole breakage is more common in hardwood than in coniferous forests, with uprooting being more prevalent in the latter. Furthermore, Larson (1963) suggested that stem taper may make conifers structurally more resistant to snap. Putz *et al.* (1983) found that in a moist tropical forest, over three times as many trees had snapped as had uprooted. Compared with uprooted trees, snapped trees often (*i*) were smaller, (*ii*) had greater height to diameter ratios, and (*iii*) had wood of lower density and modulus of rupture. After reviewing the worldwide incidence of snapping versus uprooting, they concluded that wood properties are the main factors determining whether trees uproot or snap.

### *Types of uprooting*

Uprooting, be it simple or complex, disrupts soil and later may result in the formation of a pit–mound microtopographic pair (Fig. 1). In a simple uprooting, a mound is formed on the *leeward* side of the pit (Fig. 2). Complex situations may involve various amounts of backward displacement during uprooting, with a pit possibly forming on the leeward side of the mound (Lutz and Griswold 1939; Trousdell *et al.* 1965; Pyatt 1966; Small and DuBois 1983; Beatty and Stone 1986). A type of uprooting described by Cook (1971) as *hinge-tear* is routinely observed on Histosols, where trees slowly lean as a result of low soil shear strength, gradually tearing up the organic soil as they fall (Figs. 1 and 3). The root mass may actually be connected or *bridged* to the windward side of the pit by overhanging peat, roots, and soil.

Beatty and Stone (1986) classified uprooting into two basic groups: hinge and rotational falls (see also Goodlett 1954). Hinge falls, the most common type, occur when the tree's pivot or fulcrum point is some distance from the tree base (Fig. 1, simple falls). Rotational falls involve some backward displacement during the uprooting event, the root plate becoming positioned partially or completely within the pit (Fig. 1, complex falls with backward displacement). Pyatt (1966) found that hinge falls were frequent on wet soils and rotational falls were common on well-drained soils. A thrust fall, the extreme type of backward displacement, occurs when the root mass is forced backward, completely across and beyond the pit (Trousdell *et al.* 1965; Beatty and Stone 1986). Trousdell *et al.* (1965, pp. 97–98) described two types of uprooting that can occur on very wet soils (the second not being a type of uprooting *sensu stricto*):

(*i*) Lateral roots on both sides and approximately at right angles to the direction of the wind did not fail. Trees toppled over in the direction away from the wind, pivoting on the roots that did not fail. The entire root system on the leeward side was forced into the soil as the tree toppled, forming a deep depression beneath the stump of the fallen tree. Roots on the windward side failed under tension but left little evidence of a depression on that side.

(*ii*) The stem settled into the soil below its original level, apparently under swaying wind action. When toppling, the stem appeared in some cases to have been drawn downward and backward into the soil under tension from roots that did not fail. In these cases only a slight soil elevation occurred, in place of the root mound commonly associated with windthrown trees, and no depression caused by root displacement was noted.

Additional examples are given by Stephens (1956), Rozmakhov *et al.* (1963), Armson and Fessenden (1973), Brewer and Merritt (1978), Thompson (1980), and Collins and Pickett (1982).

### *Pit-mound terminology*

Various terms have been used to describe uprooting pits and mounds. Pits have been called depressions, craters, and tip-up pits (Falinski 1978; Thompson 1980; Shubayeva and Karpachevskiy 1983). Mounds have been described as humps, hillocks, clay mounds, cradle knolls, hummocks, blowdown mounds, and (incorrectly) Indian graves; the intact root and soil mass has been variously labelled a root plate, root wad, root ball, and earth ball (Holmes 1893; Mueller and Cline 1959; Lyford and MacLean 1966; Lyford 1973; Booij 1975; Swanson *et al.* 1982; Burns *et al.* 1983, 1984; Putz 1983; Hamann 1984; Burns and Tonkin 1987). Pit and mound topography, perhaps the most commonly used term, is synonymous with *cradle knoll topography* (Lyons and Lyons 1979), *soil-windfall complex* (Shubayeva and Karpachevskiy 1983), *blow-down landscape* (Goodlett 1954), and *forest dimples* (Brockie 1977).

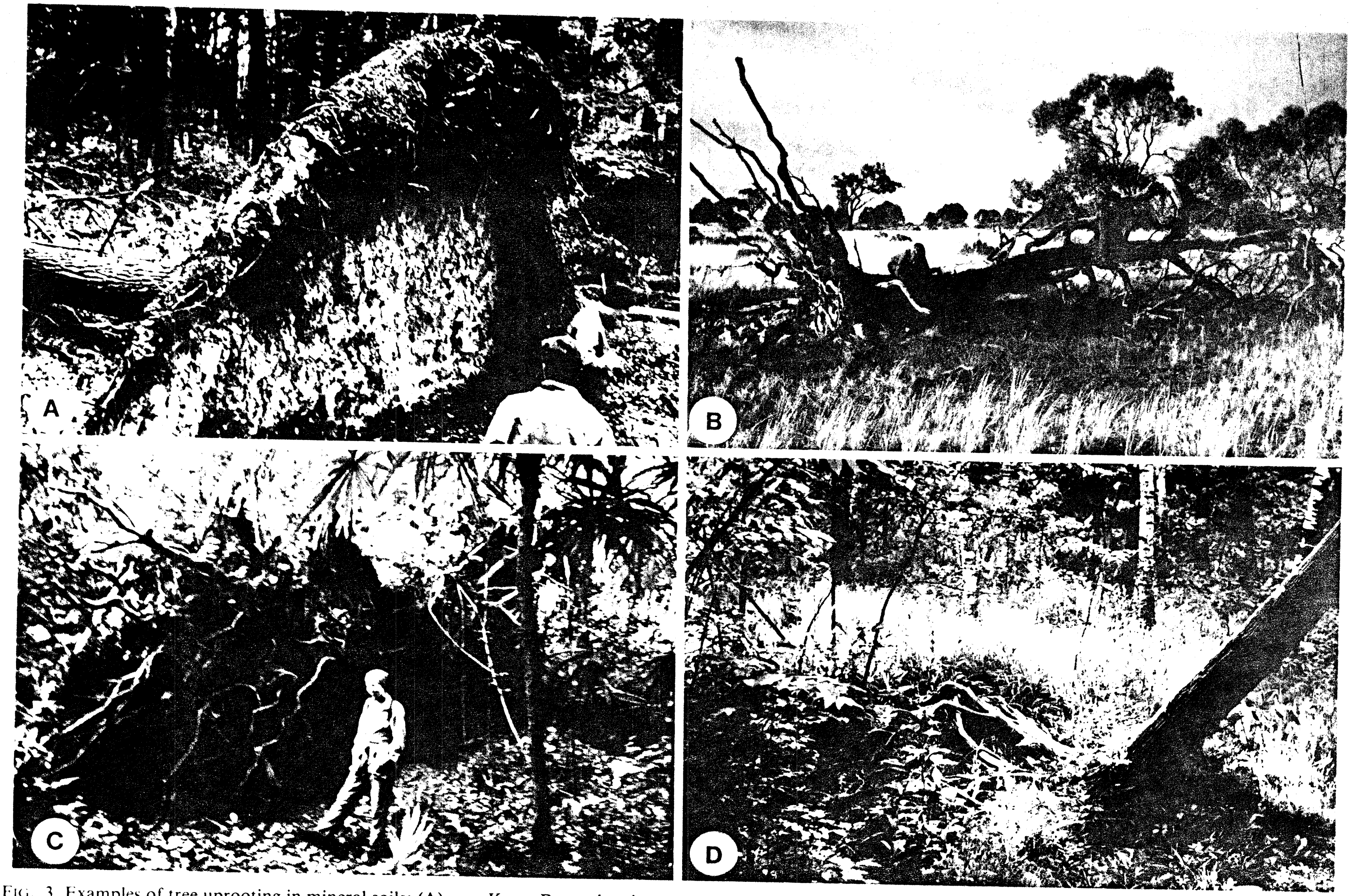

FIG. 3. Examples of tree uprooting in mineral soils: (A) near Kane, Pennsylvania, U.S.A.; (B) near Blanchetown, South Australia; (C) near the Copan area of Guatemala. (D) An early stage of hinge-tear uprooting, common in organic soils, near New Fane, Wisconsin. U.S.A.

TABLE 1. Locations and density of pit-mound topography, selected from the literature

| | Surface coverage of: | | | |
|---|---|---|---|---|
| | pits | mounds | pits + mounds | Source |
| United States | | | | |
| Great Lakes region | | | 20% | Buol *et al.* 1980, p. 270 |
| New Hampshire | | 7% | 9% | Henry and Swan 1974 |
| New York | | 7% | | Denny and Goodlett 1968 |
| Massachusetts | | | 14% | Stephens 1956 |
| | | | 25% | Veneman *et al.* 1984 |
| Pennsylvania | | | 42% | Collins and Pickett 1982 |
| Minnesota | | | Nearly 50% | Holmes 1893 |
| Kentucky | | | 0.4–2.4% | Cremeans and Kalisz 1988 |
| Oregon | | 11 mounds/ha | | Swanson *et al.* 1982 |
| Wisconsin | | 348 mounds/ha (silty soils)<br>10 mounds/ha (sandy soils) | | Nielsen 1963 |
| | | 7% | | Hole 1975 |
| Canada | | | | |
| Ontario | | | 35% | Armson and Fessenden 1973 |
| Alberta | | | 10–20% | Pawluk and Dudas 1982 |
| New Brunswick | 12% | 1255 mounds/ha | | Lyford and MacLean 1966 |
| | 1455 pits/ha | 36% | | |
| Europe and Asia | | | | |
| USSR | | | 30% | Karpachevskiy *et al.* 1968 |
| | | 20 mounds/ha | | Rode 1955 |
| | | | 10% | Shubayeva and Karpachevskiy 1983 |
| Sweden | | | 25–33% | Troedsson and Lyford 1973 |
| Other regions | | | | |
| New Zealand | | | 15–18% | Burns *et al.* 1984 |
| Panama | | | 0.09% | Putz 1983 |

The region surrounding the pit-mound pair, generally undisturbed by the uprooting event, has been used for pedologic comparisons (Stone 1975; Shubayeva and Karpachevskiy 1983; Beatty 1984; Veneman *et al.* 1984; Schaetzl 1987). The physical characteristics of pit or mound soils are compared with a type of *control* pedon. This region has been called the undisturbed pedon(s) or soil, and the zone of recent stability, the latter term recognizing that through time the entire forest floor is disturbed by uprooting.

### *Evidence for uprooting*

Many lines of evidence point to the widespread extent of treefall in forests, both catastrophic events and the nearly ubiquitous individual treefalls. Unequivocal confirmation of uprooting comes from eyewitness accounts or observations of recently fallen trees. Pit-mound topography offers important secondary evidence (Table 1).

Early reports of widespread uprooting in the virgin forests of North America come from settlers' journals; several such accounts are summarized by Goodlett (1954). Records of the U.S. Federal Land Surveyors provide an excellent means of establishing broad tracts of uprooting for the late 19th century (Stearns 1949; Siccama 1971; Lindsey 1972; Lorimer 1977; Canham and Loucks 1984), as do early geological surveys (Irving 1880; Van Hise 1904, p. 447) and historical accounts of hurricanes and tornadoes (Brooks 1940; Secrest *et al.* 1941; Smith 1946; Webster 1963; Trousdell *et al.* 1965; Wilson and Changnon 1971; Bormann and Likens 1979*a*; Small 1988).

In addition to direct evidence, proxy information has been used to estimate the extent and frequency of uprooting in presettlement forests (Stephens 1955, 1956; Henry and Swan 1974; Bormann and Likens 1979*a*; Spurr and Barnes 1980). Downed and decaying trees, with analysis of resulting canopy gaps, have been used to estimate disturbance cyclicity (Schaetzl *et al.* 1989). Jones (1945) and Thompson (1980) commented on the number of decaying boles in forests. Falinski (1978) reported that 200–450 tree trunks/100 ha accumulate annually in the Bialowieza National Park in Poland, and Naka (1982) estimated that 0.84 trees/ha are blown down annually in Japan. In the United States, treefall rates have been estimated at 0.1–0.21 trees/ha per year (Gough 1962; Brewer and Merritt 1978).

The best evidence for the universality of uprooting, at both large and small scales, is widespread pit-mound topography (Table 1). Indeed, lack of pits and mounds in forests suggests that cultivation has destroyed the microtopography (Stone 1975, p. 77). Estimates of the areal coverage of pit-mound topography range up to 50% of the forest floor (Table 1). Microrelief of pits and mounds (vertical distance from mound crest to pit bottom) ranges from near 0 to 2 m (Goodlett 1954; Troedsson and Lyford 1973; Cremeans and Kailsz 1988) and diminishes with time. Pit and mound dimensions are reported by Lutz (1940), Denny and Goodlett (1956, 1968), Nielsen (1963), Rozmakhov *et al.* (1963), Lyford and MacLean (1966), Stone (1975), Putz (1983), Burns and Tonkin (1987), and Schaetzl (1987).

TABLE 2. Estimated disturbance cycles for canopy destruction

| | Disturbance cycle (yr) | Forest type | Evidence | Source |
|---|---|---|---|---|
| Michigan | 220–2439 | *Tsuga–Pinus–* deciduous | Survey records | Whitney 1986 |
| | 1316–2632 | Swamp conifers | Survey records | Whitney 1986 |
| | 12 500–25 000 | *Pinus banksiana* | Survey records | Whitney 1986 |
| | 1587–3174 | Mixed *Pinus* | Survey records | Whitney 1986 |
| Wisconsin | 1210 | *Tsuga*-deciduous | Survey records | Canham and Loucks 1984 |
| Maine | 1150 | Coniferous–deciduous | Survey records | Lorimer 1977 |
| Illinois | 1730 | All forests | Meteorological | This study |
| New Zealand | 100–280 | *Nothofagus solandri* | Forest ecology | Wardle 1970 |

NOTE: For Michigan, Wisconsin, and Maine, the evidence is the observed incidence of treefalls in presettlement forests, as recorded in land surveyor's notes. However, Lindsey (1972) estimated that mapped windfalls in these surveys represented only 21.5% of the actual number then existing. For Illinois, the meteorological evidence is based on the incidence of tornadoes. The area of the state is 146 076 km$^2$. Assuming that the mean width and length of ground tornado paths are 177 m and 22.2 km, respectively, and the average number of tornadoes per year is 21.5 (Wilson and Changnon 1971), then every part of Illinois (on a probability basis) will be affected by a tornado within a 1730-year period. For New Zealand, the evidence is based on the forest ecology of *Nothofagus solandri* (see the cited reference for details).

### *Disturbance frequency of uprooting events*

Estimates of the frequency (disturbance cycle) of treethrow are usually based upon (*i*) forest ecology, (*ii*) statistical models of storm incidence, (*iii*) historical surveys, or (*iv*) direct observation (Table 2). The large range in estimates arises because of the lack of definition of what is being disturbed: the soil or the trees (forest canopy). *Soil* disturbance cycles are used in the case of uprooting, not bole snap, and statistically estimate the time required to disturb all soil units in a region. Brewer and Merritt (1978) estimated that a soil pedon in Michigan could be expected to experience disturbance by uprooting at least once every 3571–5000 years. Given that horizonation processes may require millennia to obliterate the homogenizing and mixing effects of uprooting, it is apparent why many forest soils show evidence of disturbance.

Disturbance cycles for the forest estimate the time necessary for treefall to affect all parts of a stand, regardless of whether the trees are uprooted or snapped. Forest canopy disturbance occurs via isolated treefall and by catastrophic blowdown (Dunn *et al.* 1983). The former type of small-scale disturbance is essentially ongoing in most forests (Schaetzl *et al.* 1989). Runkle (1982) studied rates of gap formation due to small-scale, isolated treefall. He found that canopy openings covered 9.5% of old-growth forests in the eastern U.S.A., and that new gaps were being formed annually in 1% of the canopy, yielding a natural rotation cycle of 100 years. As a comparison, Lorimer (1977) estimated that at any one time, 2% of the land surface of a presettlement forest in Maine was composed of windfalls.

Estimated lengths of disturbance cycles for nearly complete forest canopy destruction by large-scale events (hurricanes, tornadoes) are reported in Table 2. These values suggest that for forests of the mid-latitudes, disturbance by catastrophic treethrow can be expected only every 1–10 millennia. The importance of isolated treefall on the forest canopy is made evident by this comparison.

### *Factors affecting uprooting frequency and probability*

The likelihood of uprooting within a given landscape is not uniform (Cremeans and Kalisz 1988), because of spatial variability in environmental and stand factors. Wind strength is a primary factor in the prediction of treefall; numerous secondary components important in the assessment of uprooting potential are discussed here.

Anything that inhibits deep rooting, such as a fragipan, excessive stoniness, shallow bedrock, a clay-rich B horizon, a "plow pan," iron pan, a subsurface horizon of high bulk density, a high water table, or toxicity in lower horizons, makes trees more susceptible to uprooting by impeding root development (especially of vertical roots) (Hubert 1918; Jacobs 1936; Ruth and Yoder 1953; Gratkowski 1956; Mueller and Cline 1959; Lyford *et al.* 1963; Fraser and Gardiner 1967; Olson and Hole 1967; Faulkner and Malcolm 1972; Laffan 1979; Adams and Moore 1983; Small 1988). Nielsen (1963) summarized environmental factors that may interact to determine the density and size of uprooting mounds in an area: (*i*) water table, (*ii*) subsurface pans (e.g., duripans, fragipans), (*iii*) solum thickness, (*iv*) rooting habits, (*v*) storm tracks, (*vi*) slope, (*vii*) frozen subsoil, (*viii*) vegetational history and condition of the tree overstory, (*ix*) soil texture, and (*x*) faunal activity.

Fraser (1962) and Wilson (1976) have demonstrated that expanded rooting depth leads to considerable increases in resistance to uprooting. For example, 51% of trees on soils with restricting layers experienced damage during a hurricane, compared with only 7% on soils without root-restricting horizons (Trousdell *et al.* 1965). Croker (1958) reported that 90% of the longleaf pine trees uprooted by Hurricane Flossy were on soils with shallow clay pans; these soils occupied only 46% of the study area. Soils with deep pans composed 25% of the surface, but had only 3% of the windthrown trees.

Trees growing on wet, gleyed or organic soils are more likely to be uprooted than those on better-drained sites, because of shallower rooting and decreased soil shear strength when wet, and increased incidence of root rots (Hubert 1918; Behre 1921; Gratkowski 1956; Mueller and Cline 1959, p. 107; Fraser and Gardiner 1967; Pyatt 1968; Faulkner and Malcolm 1972; Kennedy 1974). Saturation of otherwise freely draining soils, coupled with strong winds, can lead to widespread uprooting through decreased shear strength of the soil (Hubert 1918; Curtis 1943; Day 1950; Croker 1958; Trousdell *et al.* 1965). For example, uprooting appears to be the major type of damage incurred when hurricane winds are preceded by strong rains; when little rainfall occurs the damage involves mostly broken and bent trees (Trousdell 1955). Conversely, Savill (1976) cited evidence that drainage of wet, gleyed soils does little to encourage deeper rooting, because of slow oxygen diffusion into the subsoil. In a similar vein, drainage of peat soils may increase resistance to uprooting by promoting deeper rooting (Fraser 1962). Pyatt (1966) found that root systems of 27-year-old Norway spruce (*Picea abies*) were 91–168 cm deep when growing in well-drained soils and 30–48 cm deep in poorly drained sites. His study also suggested that thinning of trees on wet soils increases root spread, but does not appear to increase resistance to uprooting because vertical root growth is temporarily inhibited.

Pathogens that weaken the root system of trees increase the likelihood of uprooting. Fraser (1962) suggested that *Fomes annosus* root rot reduces a tree's resistance to uprooting by 30% or more. Gratkowski (1956) documented the importance of root and butt rots as factors leading to uprooting, and trunk rots as factors promoting bole breaks. Hubert (1918), in an early review of the interactions among fungi, wood rots, and tree stability, noted the very strong correlation between uprooting in older stands and fungal infestations.

Shallow-rooted genera such as *Picea, Abies*, and *Pinus* are prone to uprooting (Hubert 1918; Day 1950; Rozmakhov *et al.* 1963; Faulkner and Malcolm 1972; Pritchett 1979), although on deep, porous soils they are more windfirm (Pyatt 1968; Wilson 1976; Somerville 1979). Matthes (1911) found that *Picea* is more windfirm when growing near lupine and alder, because the root system of *Picea* is stimulated to expand in search of nitrogen that is being fixed by the alder and lupine.

Examples of windfirm genera include *Quercus, Acer*, and *Tsuga* (Curtis 1943; Veneman *et al.* 1984), although in some regions *Tsuga* species are prone to windthrow (Baker 1915; Ruth and Yoder 1953). Brewer and Merritt (1978) found that no one species was more prone to uprooting than any other in a *Fagus–Acer* forest. Harcombe and Marks (1983) reported that over a 5-year span, 77% of the trees in a *Fagus–Magnolia* forest in Texas died before falling, 21% snapped, and none uprooted. Hubert (1918) suggested that taprooted species were more susceptible to snap than to uprooting.

A tree's shape and size influence the forces exerted upon it by the wind. Larger and older trees tend to be more susceptible to uprooting and bole break than their younger counterparts (Smith and Weitknecht 1915; Hubert 1918; Dunn *et al.* 1983; Jane 1986). For this reason, uprooting and bole break are relatively uncommon in young stands (< 100 years old), except during violent windstorms. Burns (1981)[1] found that some roots of *Nothofagus solandri* begin dying after the trees reach 25–30 cm DBH, leading to instability and uprooting. The tall, slender growth habits of trees such as *Pinus contorta* also lead to increased uprooting hazard (Mason 1915).

Exposure, slope, and elevation are also important variables in the determination of uprooting potential (Curtis 1943; Dixon and Place 1952; Ruth and Yoder 1953; Fraser 1962; Alexander 1964; Palmer 1968; Kotarba 1970). Trees growing on steep slopes are often tilted and therefore may be prone to uprooting. In general, more wind damage occurs on exposed upper slopes and in sites where winds are funnelled and concentrated (Hubert 1918; Jensen 1939; Gratkowski 1956; Jane 1986), although in certain site contexts, sheltered coves may be most susceptible to uprooting because of concentrated subsurface water (Cremeans and Kalisz 1988). Uprooting in Ireland and Great Britain, uncommon below 50 m elevation, is a major hazard at elevations above 150 m (MacKenzie 1976; Booth 1977). Uprooting of trees growing at or near alpine treeline is relatively rare, however, primarily because of (*i*) small stature, (*ii*) wide, spreading root systems, (*iii*) more leaders per tree, (*iv*) lowered incidence of snow-down because of "dry" snow at high elevations, (*v*) continuous exposure to strong winds, and (*vi*) slow growth rates, leading to greater wood density and strength (Reiners and Lang 1979; Tranquillini 1979; Burns 1981 (see footnote 1); Jane 1986). Trunk break and wind shaping is more common at treeline than is uprooting (Yoshino 1973; Cremeans and Kalisz 1988).

Lutz (1960) noted that trees growing in very rocky soils are not as windfirm as those rooted in deep, stone-free soils, although Hubert (1918) and Jane (1986) felt that the opposite was true. Lutz ascribed this to (*i*) lack of bracket roots on one or more sides of the stump in stony soils, and (*ii*) compression failure of bracket roots when stones prevent the roots from moving downward as the tree sways in the wind (see also Moore 1933 and Mergen 1954). Stone (1977) noted that repeated wind sway of tree trunks, a precursor to uprooting, can lead to root xylem damage, bruises, and ruptures in rocky soils (see also Fayle 1965 and Hintikka 1972). Trousdell *et al.* (1965) found that hurricane damage in pine forests was significantly greater on soils with coarse textures than on those with finer textures. Small (1988) studied thin (20–50 cm thickness) and wide (up to 7.5 m diameter) root plates of 300- to 400-year-old uprooted trees in Pennsylvania, and ascribed their shape to shallow fragipans.

### *The silvicultural and economic importance of uprooting*

Storms annually destroy millions of board feet of timber (1 board foot = 2359 $\text{cm}^3$) in the United States alone. Several examples of catastrophic blowdown have been described. The "great windfall of September 1872" (Irving 1880), which occurred in northern Wisconsin, was more than 65 km in length. Storms in 1933, 1934, and 1936 on the Menominee Indian reservation in Wisconsin blew down an estimated 80 million board feet of timber, 30–40 million board feet in one storm (Heritage 1939; Secrest *et al.* 1941). A 1977 downburst in north central Wisconsin levelled 344 000 ha of forest, causing damage estimated at $50 million (Taylor 1978; Dunn *et al.* 1983). Its blowdown path averaged 24 km in width and over 200 km in length. In the Siuslaw National Forest, Oregon, 3.7 billion board feet of timber were damaged in a blowdown event (Ruth and Yoder 1953). The Mount St. Helens eruption of May 18, 1980, flattened 500–600 $\text{km}^2$ of forest (Kieffer 1981; Findley 1981). Most of the trees were uprooted, rather than having their trunks broken above the soil surface. The Tunguska meteor and its shock wave, which struck Siberia in 1908, levelled trees over a vast area (Krinov 1966).

Uprooted trees and broken boles often cannot be salvaged for lumber because of the twisted internal structure and

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[1] S.F. Burns. 1981. Windthrow in a mountain beech forest, Craigieburn Range, New Zealand. Preliminary report to the Forest Research Institute, Ilam, N.Z.

weakened state of the wood (Trousdell 1955). Even if the trees are salvaged, the forester often incurs economic losses as a result of timber breakage and increased logging (recovery) costs (Hubert 1918). To minimize both economic losses and fire risk, the downed tres must also be harvested quickly (Taylor 1978).

Several authors have reviewed the interrelationships of uprooting and silviculture. Gratkowski (1956), Alexander (1964), and Curtis (1943) examined wind damage in forests and discussed several ways in which such disasters can be minimized by using foresight in cutting, thinning, planting, and plowing practices (see also Hubert 1918; Day 1950; Ruth and Yoder 1953; Yeatman 1955; Boe 1965; Fraser and Gardiner 1967; and MacKenzie 1976). Savill (1976) discussed how site preparation and drainage of wet soils affect the potential for uprooting. Palmer (1968) edited a volume dedicated to the effects of wind on forests and the methods by which forests can be properly managed to minimize the hazard (see especially Hutte 1968 and Stumbles 1968). Spaltenstein and Ugolini (1987) recommended that foresters in the *Picea-Tsuga* forests of Alaska till the soil after logging to mimic the mixing processes of uprooting, by which nutrients beneath dense Bh horizons are brought to the surface. Failure to mix the soils, either by uprooting or by tillage equipment, often results in the eventual degradation of the forest to a low-productivity muskeg.

Pyatt (1966) devised a scheme whereby the time and location of uprooting could be forecast by employing information on soils, topography, and stocking (i.e., a stand map). Using this information, he was able to determine three zones of windthrow susceptibility: (*i*) sheltered zones on lower slopes with deep, well-drained soils, (*ii*) moderately exposed zones of middle slopes with poorly drained soils, and (*iii*) wet soils of very exposed zones of upper slopes and hill crests. Reiners and Lang (1979) found that canopy gaps in mountainous forests of New England were most common below summits on southeast-facing slopes, where snow transported from windward slopes accumulates. Fraser and Gardiner (1967) were able to predict critical heights above which treethrow can be expected. That stocking is important to windthrow susceptibility has been demonstrated by several researchers, who determined that damage to loblolly pine plantations from Hurricane Donna in 1960 was more severe in thinned than in unthinned stands (Trousdell *et al.* 1965; see also Nelson and Stanley 1959).

It is also important to note the economic impact of pit-mound microrelief, in and of itself. Hummocky microrelief increases the cost of logging operations by hindering vehicle movement (Beke and McKeague 1984). Clearing of forest land for agricultural purposes is more costly if pit-mount microrelief is common. Lastly, wet soils in pits may promote the development of tree diseases and inhibit mycorrhizal development (Lorio and Hodges 1971).

Practices and factors that appear to result in increased resistance to uprooting are (*i*) using foresight in thinning and cutting, especially clear-cutting, (*ii*) minimizing damage to roots during logging operations, (*iii*) "conditioning" of trees to strong winds, (*iv*) draining of wet soils, and (*v*) mechanically breaking up subsurface pans and impermeable horizons (Hubert 1918; Behre 1921; Jensen 1939; Curtis 1943; Day 1950; Gratkowski 1956; Fraser 1962; Alexander 1964; Palmer 1968; Somerville 1979).

## Conclusions and future work

Research on tree uprooting has been conducted for over 90 years, and terminology abounds. Researchers need to be consistent in their use of terminology, and avoid developing new terms.

Uprooting is important in the forests of the world because it affects soil morphology, surface characteristics, nutrient availability and cycling, regeneration trends, and forest age structure. Research on the problem has centered on the temperate forests of the world, especially in the northeastern and north central United States. Much has been learned about the process in both virgin and cultivated-cutover forests, where uprooting is an economic burden. Foresight in silvicultural practices has reduced the effects of treethrow in some regions, especially Great Britain and New Zealand. Given the predominance of uprooting research in temperate regions, there is a pressing need for data from other forests of the world, especially the temperate forests of Africa and South America, and tropical forests in general. Furthermore, little uprooting research has been attempted in cold coniferous forests of alpine and arctic regions. Studies showing the importance of uprooting to the total forest ecosystem are needed. The role of pathogens in reducing root strength must also be explored.

Future work should closely examine the relationships between site and windthrow hazards. For example, species that appear to be windfirm in one site context may be highly prone to uprooting elsewhere. Determining incidence of windthrow in numerous landscape situations could allow for the development of windthrow susceptibility indices for both species and site. Certainly, endogenous factors such as tree height and age should also be included in the analysis. Taken one step further, these interrelationships may best be determined by calculating correlation matrices among several environmental factors, and by further testing of these statistical relationships in the field.

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