Pedoturbation

Martin V. Fey
University of Pretoria, South Africa

Randall J. Schaetzl
Michigan State University, USA

The term "pedoturbation" refers to processes by which soil is physically mixed or disturbed. Although its chief cause would seem to be biological, in the form of digging animals and falling trees, a diverse range of processes can actually lead to soil mixing, many of which are abiotic. Indeed, soils can be mixed by a wide variety of vectors, such as freeze–thaw and shrink–swell activity, seismic shaking, slope failure, and even exploding bombs. And although, historically, pedoturbation has been associated with profile simplification, it is now viewed as a process that does not always destroy but may sometimes form and maintain genetic soil horizons. Although long underappreciated and only minimally studied, pedoturbation is a measurable process in almost all soils, and has important consequences for soil genesis, properties, and behavior.

Expressions of pedoturbation

In its various forms, pedoturbation is studied either by observing the process (such as termites digging tunnels and, in so doing, moving soil particles) or by examining and interpreting the end products of pedoturbation within the soil itself. Signatures of pedoturbation are primarily expressed as within-profile, morphological imprints and as surface topographic features. Within-soil expressions include slickensides, fecal pellets, microfabric alterations, stone lines, broken and disrupted soil horizons, and open and infilled burrows (krotovinas). Because many forms of pedoturbation cannot effectively move larger fragments upward in soils (with tree uprooting and freeze–thaw activity being the major exceptions), they tend to settle and become concentrated at the lowermost depth of the process, as a stone line or zone. This type of depth distribution of coarse fragments is commonly used to infer long-term pedoturbation in the upper parts of a soil. Surface expressions of pedoturbation occur as microrelief such as gilgai, tree-throw mounds and pits, ant and termite mounds, patterned ground, and depressions associated with caved-in krotovinas.

Agents of pedoturbation

Types of pedoturbation are identified by the vectors that cause them. The list of such vectors, originally compiled by Hole (1961) and expanded on by Johnson *et al.* (1987), includes faunal- (animals), floral- (plants), gravi- (soil movement under gravity), congeli- or cryo- (freeze–thaw cycles), argilli- (shrinking and swelling of clay minerals), seismi- (earthquakes), aero- (passage of air, wind), aqua- (passage of water through soil), crystal- (rupture by growth of salt and other types of crystals) and impact- (comets and meteorites) turbation. To these, Hupy and Schaetzl (2006) added bombturbation. Normally, the term bioturbation is given to mixing by biota, including plants and/or fauna.

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Bioturbation has received more attention than perhaps all other forms of pedoturbation combined (Wilkinson, Richards, and Humphreys 2009). Each of these agents/vectors may be prominent in some environments and negligible in others.

In most cases, pedoturbation is associated with increases in soil volume and porosity, and with concomitant reductions in bulk density. Positive feedback can readily be imagined, especially with respect to bioturbation – as habitation opens up the soil, rendering it even more habitable for bioturbators. Synergy of other kinds, between various pedoturbation vectors, may also occur, for example, the combination of high precipitation, steep slopes, deep weathering, and giant trees in the humid tropics results inevitably in isotropy or haploidization – minimal differentiation of the soil profile into recognizable horizons (Hole 1961). The following sections briefly cover some abiotic processes of pedoturbation, eventually focusing on the role of biota in pedoturbation, given the prime function of soil as terrestrial habitat for biota. Biotic processes also include past and future human activities, which disturb soil for better or for worse (anthropoturbation).

Abiotic processes

Although bioturbation is the most commonly viewed and studied form of pedoturbation, many other forms also exist, and most of these are abiotic in nature. For example, in graviturbation, soil moves from elevated upland positions to bottomlands by piecemeal erosion or mass movement processes. This movement can be imperceptibly slow (as surface wash and soil creep) or catastrophic (in the form of debris flows and landslides). Any degree of mixing can occur during these processes. The end results of such mixing are evident in the colluvial or alluvial end products near the bottom of slopes. Textural sorting may be evident here, although not easily distinguishable from that of animals. Mass movement can also be triggered by seismic activity, in which case it is considered a type of seismiturbation.

Climate is an important mediator in all forms of pedoturbation, even the abiotic ones. For example, the flow of water on and within soils can mobilize the solid constituents within, causing mixing. Water is an agent of volume change in soils, as enacted by the swelling of wetted clays or the expansion of ice crystals. It is also a generator and concentrator of salts through weathering, leaching, evaporation, and crystallization. Soil mixing caused by the growth of such crystals is called crystalturbation. The pedogenic development of Vertisols is a celebrated example of abiotic pedoturbation by the expansion caused as smectite clays wet up (Jackson 1965; Southard, Driese, and Nordt 2011). In wet dry climates, such soils undergo many cycles of wetting and drying, causing volume changes and churning of the soil profile; this form of pedoturbation is called argilliturbation.

Abiotic influences on pedoturbation are also, in turn, mediated by biota. Rates of infiltration, for example, are affected by faunal burrowing, and by vegetation cover which reduces raindrop impact. Less surface runoff means reduced sheet erosion, but it also makes mass movement more likely because of the increased incidence of saturation.

Biotic factors

Floralturbation (soil mixing by plants) is largely accounted for by the mixing that occurs when trees are uprooted (Hole 1961; Schaetzl *et al.* 1990; Šamonil, Kral, and Hort 2010). In this case the real agents are wind and gravity, with the tree itself playing a passive role. Trees tear up soil as they uproot, often forming a pit at the former location of the roots, and an adjacent mound, located where the soil slumps off the roots. Soil materials within the mound can be extremely mixed, although in some cases, they are simply overturned in a more or less intact manner (Schaetzl 1986).

A spectacular example of tree uprooting can be observed where rainforest occurs on bauxite terrain in the interior of Guyana. Here, to a depth of about 2 m, the soil consists of a friable brown earth containing abundant, angular, disoriented fragments of saprolitic bauxite (Figure 1a), below which the saprolite shows an inherited jointing pattern, indicating preservation in situ. When wet, the tree canopy becomes top-heavy and the anchoring substrate loses much of its coherence, needing only a light breeze to topple the trees and tear up deep bauxite fragments. The disorganized morphology of the upper bauxite profile is therefore often attributed to uprooting. Loose surface gravels above hard laterite in the ancient jarrah forest of the Darling Range in Western Australia are possibly due to a similar mechanism, in which the laterite cap is progressively broken up by roots of falling trees (Figure 1b).

In southern Africa, a noteworthy accessory agent of floralturbation by uprooting is the elephant. In pushing trees over while foraging, elephants indirectly create a surface armoring of uprooted gravel in terrain with pedogenic calcrete (Figure 1c). The surface armor forms as the uprooted soil slowly erodes, leaving the coarse fragments at the surface as a lag concentrate. This example shows how flora and fauna may combine to mix soils, as well as illustrating that most soil processes are both biotic and abiotic in nature. The way in which animals interact with the plants on which they forage has many examples, especially among rodents and pigs which burrow for roots, bulbs, and truffles. Some rodents, such as North American gophers and Southern African mole rats, live belowground in large family groups and have extensive tunnel networks. The constant bioturbation they cause is easy for the casual observer to miss.

(a)

Figure 1 Examples of floralturbation by tree uprooting in contrasting environments. (a) The top 1 m of lateritic bauxite profiles in the Kopinang district of Guyana consists of randomly broken bauxite fragments mixed with a friable, earthy matrix. (b) Roots of fallen giant jarrah trees (*Eucalyptus marginata*) in the Darling Ranges, Western Australia, exhume large fragments of the laterite hardcap. (c) The combined effect of animals and plants near Lake Etosha, Namibia. Thorn trees (*Vachellia* sp.) pushed down by foraging elephants break up the pedogenic calcrete layer, eventually leading to armoring of the soil surface with limestone fragments. (Photos by Martin Fey.) *Continued opposite.*

(b)

(c)

Figure 1 *Continued*

Figure 2 Termite mounds on an open grassy *dambo* (marshland) in northwestern Zambia (photo reproduced by permission of Tamara Knudsen).

Floralturbation is not always passive. The emergence of seedlings and the growth and death of plant roots are examples of active floralturbation processes, even though their scale is small compared to that of tree uprooting.

Faunalturbation (soil mixing by animals) is perhaps the most conspicuous category of soil mixing, with the greatest diversity of expression. Every continent has its own evolved assemblage of small and large animals that either live underground or dig, burrow, and scratch in the soil for various purposes, for example worms, insects, spiders, snakes, frogs, birds, and mammals (Johnson *et al*., 1987; Fey, Milewski and Mills 2010; Fleming *et al*. 2014). Quite likely, the largest overall amount of faunalturbation is produced by smaller animals, especially earthworms, ants and termites (Figure 2) – an observation that even Charles Darwin (1881) noted. Associated with the activity of these smaller fauna are the burrowing and nutrient-cycling effects of larger animals that prey on them. Their digging is additional to that of animals that forage for vegetable matter and of still others that simply make their home in the soil.

Figure 3 Mima mounds at the Mima Prairie in Washington State, USA (photo reproduced by permission of Diana Johnson).

Mima mounds are a famously controversial surface expression of bioturbation. Named for the Mima Prairie in Washington State, United States, Mima mounds are dome-shaped earth mounds, often >2 m high and 10–50 m in diameter (Figure 3). They are widespread on many grassland landscapes and can cover vast acreages at densities exceeding 100 ha^{-1}. Mima mounds occur only on soils shallow to bedrock or a subsurface pan, such as a duripan, or in soils that have high water tables (Horwath Burnham and Johnson 2012). The origin of these features has long been controversial, and many have attributed their formation to abiotic processes. Modes of origin include wind and water erosion of intermound lows, sediment accumulation at the sites of individual plants (shrubs or clumps of grass), trapping eolian or fluvial sediment, and paleoperiglacial origins, like Arctic stone circles, in large part because areas between the mounds were often bare of vegetation and strewn with large rocks. The fossorial rodent hypothesis of Mima mound origin, widely accepted today, was in fact once ridiculed. In this hypothesis, Mima mounds are formed as pocket gophers or similar burrowing rodents, for example moles or tuco-tucos, tunnel outward (not so much downward), pushing soil material behind them and building up a mound. The mounds serve as nesting chambers in the thin or wet soils, providing the increased soil thickness necessary to protect them from predation, winter cold, or high water tables. Because these animals are so territorial, their mounds come to be located almost in perfect, regular arrangements on the landscape. Where soils are thick, gophers are not restricted in siting their nests; thus, they move from place to place, burrow more deeply, and mounds per se are not formed. Between the mounds one commonly finds a zone where soil is thin and rocks are numerous; the rodents have removed the soil from these areas. The mounds contain small stones only, equal to the size that the rodents can carry upward. Stone lines containing stones too large for gophers to move (>≈6 cm diameter) commonly underlie and ring the mounds. Thus, the mounds are essentially over-thickened biomantles formed by point-centered burrowing (Horwath and Johnson 2006).

Mounds similar to Mima mounds are conspicuous over large areas of the African continent. In South Africa they are locally known as *heuweltjies* (Afrikaans) or *isiduli* (Zulu), and termite activity seems to be central to their formation (Fey, Milewski and Mills 2010), although, as is the case with Mima mounds, more than a single factor may be involved (McAuliffe *et al.* 2014).

Bioturbationally mixed parts or layers in soils are referred to as biomantles. Usually, a biomantle represents the upper part of the soil that is or has been thoroughly mixed and disturbed by biota (Johnson, Domier, and Johnson 2005). The idea of the biomantle was perhaps first introduced (but not named as such) by Charles Darwin (Johnson 2002). Johnson, Domier, and Johnson (2005) have argued that the role of animals in soil formation has until quite recently been underestimated because of the agricultural orientation of soil science. Especially useful is their honing of the concepts of proisotropic and proanisotropic pedoturbations, giving rise to regressive and progressive expressions of soil development, and resulting in soil profiles becoming either haploid (simple) or differentiated (horizonated), respectively.

It is appropriate to include all types of human activities in the category of faunalturbation. Human actions include the ploughing and draining of farmland, diverse urban excavations and cut and fill operations, mining and reclaiming of mined lands, and various land-use practices that accelerate soil erosion. Some of these activities can fall under the rubric of pedoturbation. Anthrosols and Technosols are two groups of soils defined in the World Reference Base for Soil Resources (FAO 1998), that accommodate soils with properties markedly affected by human activity, some of which would involve mixing or *anthropoturbation*. The human factor may also have operated negatively with respect to bioturbation, because much human activity has led to a decline in the number and species of animals, that is bioturbators, in most environments.

Consequences of pedoturbation

Of all the effects which soil mixing and disturbance produce, perhaps the most important involves soil structure and, more specifically, its corollary, soil porosity. Soil without pores would be lifeless. Porosity, pore size distribution, and the connectivity of pores all contribute to life-sustaining functions of soils such as the infiltration, storage, and discharge of air and water, including both nutrients and gases that may be either necessary or harmful. Furthermore, the penetrability of soil by roots and burrowing animals is mediated by porosity, which imparts a softer, more friable consistence to soils, especially finer-textured soils. Some clay soils such as Oxisols are highly porous. Others, such as Vertisols, are dense, compact, and deficient in functionally useful pores, except for either extremely fine ones that inhibit water uptake by plant roots, or wide transmission cracks that allow rapid water infiltration into dry soil but close up soon after wetting. In Oxisols, porosity generated by the deep burrowing and construction activity of small fauna, especially termites and ants (Reatto *et al.* 2009), is preserved through a combination of soil climate and clay mineralogy which results in minimal shrinkage and swelling, and negligible clay dispersion. In Vertisols and related clayey soils, mixing by swelling and clay dispersion (argilliturbation) likely combine to destroy larger soil pores not long after they have been generated via bioturbation. Shrink–swell cycles also create ephemeral porosity in the form of spaces between peds, which are most evident when the soils are dry.

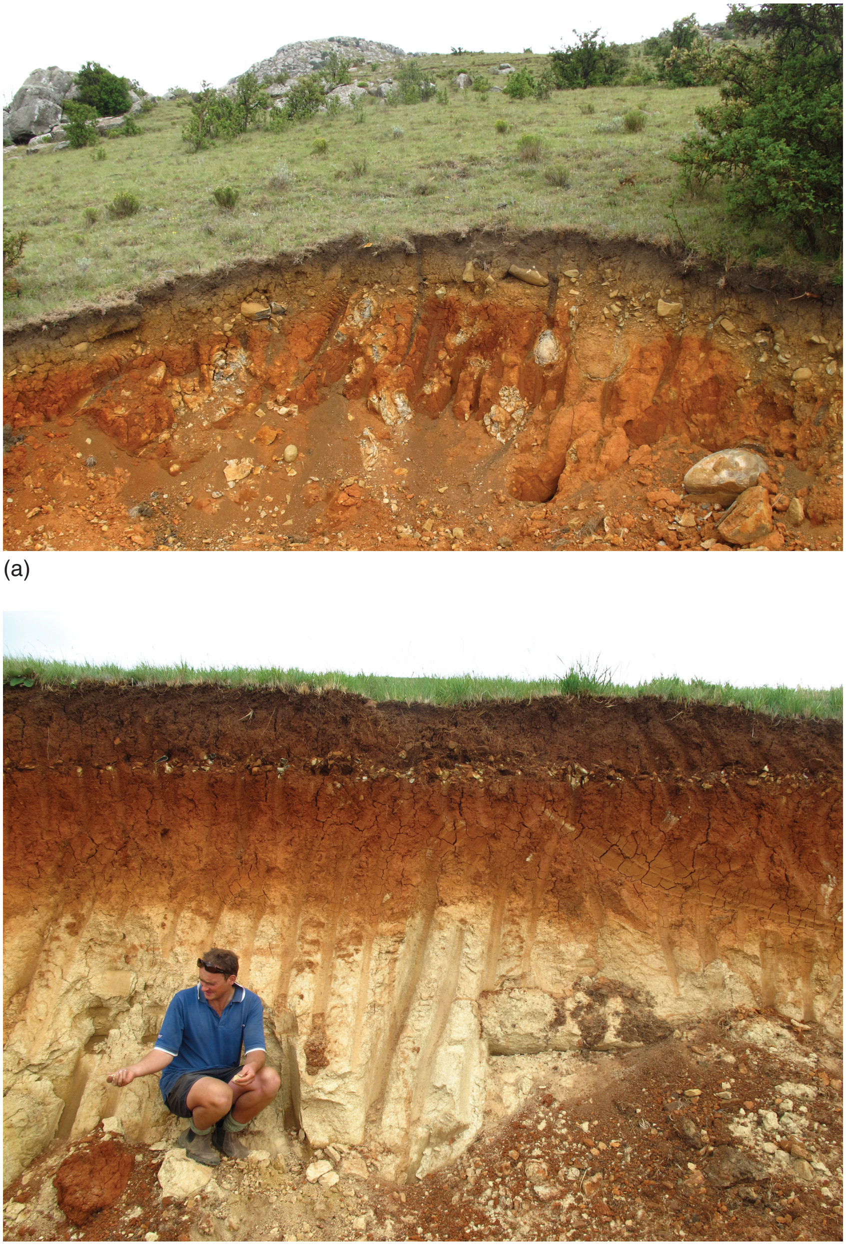
A number of other, secondary consequences of soil mixing also stem from the development of soil porosity. Many of these take the form of feedback loops, through which pathways of development, having crossed a pedogenic threshold, become increasingly divergent. The clay minerals that characterize the Oxisol–Vertisol catena derived from mafic rocks in tropical landscapes are promoted by the flushing of silica and bases from the Oxisol and the accumulation of these solutes in the Vertisol (Jackson 1965). In considering the chemistry of such pedogenic divergence, it might be interesting to assess the contribution made by pore-initiating soil biota.

Pedoturbation has other interesting consequences. In agriculture, there is increasing awareness of the fuel-saving and soil structure-preserving benefits that may accrue from minimal tillage or no-till farming. In reality, soil tillage does not cease with no-till farming; it continues, but in the form of biotillage, driven by bioturbators and fueled by crop residues. Worms and other soil fauna do the work of tractor and plow. In repairing landscapes disturbed by mining, the long-term stability of restored vegetation hinges on the extent to which a new ecosystem can be established, including soil organisms, especially burrowers that can counter the effects of human-induced soil compaction. Water yields from catchments are affected by faunal pedoturbation, including preferential subsurface flow through krotovinas. The ways in which bioturbation affects land use and ecosystem function are reviewed by Wilkinson, Richards, and Humphreys (2009). The development of subsurface stone lines below a biomantle, as is so common in many landscapes (Nye 1954; Johnson *et al.* 1987; Figure 4), is of special interest to archaeology because human artifacts are often included in these stone lines.

Other consequences of pedoturbation in its broader sense are those of an engineering nature. Landslides produce characteristic soil morphology that can serve as a warning to builders. Slickensides, cracks, self-mulching, and gilgai microrelief are all indications that the site may be unsuitable for construction due to argilliturbation. And the presence of cryoturbation (frost heave) may sometimes also be revealed by characteristic spatial patterning (Johnson *et al.* 1987).

Theoretical considerations regarding pedoturbation

For decades, soil science has focused on how pedologic order (anisotropy, soil horizonation) can evolve from sediments that were initially disordered, isotropic parent materials such as loess or dune sand, or ordered, anisotropic ones such as stratified alluvium. Parallel to this, the notion that pedoturbation is a regressive soil process – one that blurs soil horizons or prevents them from forming – has also been historically



(a)

(b)

Figure 4 Stone lines marking the boundary between the fine earth-textured, humus-rich biomantle above, and underlying B horizon containing weathered saprolite. The soils shown here are both derived from gabbro on the Nolangeni Mountain near Kokstad, South Africa. Buried artifacts, originally left on the surface by paleo-peoples, are lowered by bioturbation and thus are commonly encountered in such stone lines. (Photos by Martin Fey.)

dominant. Few studies prior to 1960 concluded that pedoturbation can actually create, or even preserve, the anisotropy that often directly results from pedogenesis. Thus, pedoturbation has traditionally been viewed as a process that destroys horizons or that acts to slow or reverse horizon-forming processes.

Current research has found, however, that pedoturbation can also form horizons, or at least be neutral with regard to horizonation processes. Thus, Hole (1961) and Johnson *et al.* (1987) classified pedoturbation into one of two categories: proisotropic or proanisotropic. The former term implies a condition tending toward (pro) isotropy or disorder, while proanisotropic pedoturbation means a tendency toward layering and order. Proisotropic pedoturbation disrupts, blends, or destroys soil horizons and geologic layers, or impedes their formation. When this type of pedoturbation dominates a soil, a morphologically simplified profile evolves from a more ordered one. Proanisotropic pedoturbation forms or maintains soil horizons and geologic layers, usually causing an overall increase in profile order.

Seldom are pedoturbation processes entirely proisotropic or entirely proanisotropic. Instead, they usually have elements of both, with one form of pedoturbation often being more strongly expressed than the other. Most soils have components of each of these two sets of interacting processes. The balance between the two ultimately determines the morphological makeup of the soil. For example, earthworms may mix organic litter into the A horizon, and in so doing blur the two horizons – a proisotropic phenomenon. But, by doing this, the worms thicken the A horizon at the expense of the litter layer above, thereby promoting horizonation – a form of anisotropic mixing. The expression of this suite of processes is a soil with a slightly thicker A horizon.

Conclusions

Soils are constantly in a state of flux. The flux can be turbulent and catastrophic, but for most of the time and in most places it is barely perceptible, permitting stable anchorage for the growth of plants, shelter of animals, evolution of ecosystems, and the emergence of prosperous agricultural communities. And yet, in such settings, pedoturbation of various sorts may be ongoing almost continually, although usually unseen, below the surface, and in the background. In other landscapes, such as those grasslands where Vertisols dominate, or the tundra where evidence of frost churning is everywhere, the importance of pedoturbation is clear, omnipresent, and less likely to be underestimated.

Normally, pedoturbation rejuvenates and refreshes the soil. Only rarely does it constitute a hazard. Future research could profitably explore the extent to which the soils we study owe some of their attributes to pedoturbation. These attributes may disappear if the flux is not maintained or may have done so already because pedoturbation has ceased. On the other hand, traditional soil tillage may be seen as a substitute for natural pedoturbation but it may in the long run be insufficient to maintain the soil porosity needed for profitable agriculture.

SEE ALSO: Biogeomorphology; Soil biology and organisms; Soils in archaeological research; Soils in geomorphic research

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