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Differing views of soil and pedogenesis by two masters: Darwin and Dokuchaev

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ABSTRACT

Charles Darwin and Vasily Dokuchaev made early and important, but quite different, contributions to pedogenic theory. Their major contributions were both written as books — Darwin's, 1881 *The Formation of Vegetable Mould, Through the Action of Worms, With Observation on Their Habits*, and Dokuchaev's, 1883 *Russian Chernozem*. Although most soil scientists are familiar with Dokuchaev's legacy and lasting impact, far fewer know about or value equally Darwin's “worm book.”

Dokuchaev's factorial approach to soil science, drawn from observations across the Eurasian steppe, helped map, classify, and place economic value on soils, while also providing key insight into their formation. This approach gained visibility in the 1930s and 1940s, when personnel at the U.S. Department of Agriculture, and some academic pedologists, recognized its utility for soil survey and for interpreting pedogenesis. Jenny's (1941) book, *Factors of Soil Formation*, helped the model to gain acceptance, and it eventually became entrenched as the core pedogenic model for North America, if not the world. Dokuchaev's legacy is tied to this model. Alternatively, Darwin's main contribution to the field was to shed light on soil processes, particularly faunal mixing (bioturbation) and the textural sorting it can produce. Although Darwin's findings fostered an array of multidisciplinary studies on pedogenic processes during the ensuing 50 years, his work languished in the broad shadow cast by Dokuchaev's model. In 1975, Darwin's ideas reappeared in *Soil Taxonomy* — associated with rudimentary biomantle concepts. Recently, empowered with new concepts and language, bioturbation concepts have gained considerable traction.

We briefly summarize the backgrounds of Darwin and Dokuchaev, and compare their fundamentally different approaches to pedogenesis. But insofar as Dokuchaev's approach is more mainstream, we emphasize Darwin's, for balance. We show how Darwin's model, updated with current understandings of biomantle formation, is allowing new questions to be asked about pedogenesis and landscape evolution, and formerly intractable ones to be answered. We stress the profound role of conceptual models in guiding explanatory thought, and end by positing that both Darwin's and Dokuchaev's approaches, while different in their basic structure and goals, provide together a more complete view of pedogenesis than either can do singly.

“At … Rothamsted [Research Station in England] there is a field which has not been ploughed for three hundred years, and on which is nine inches of fine brown loam overlying a layer containing flints … The overlying nine inches has been presumably brought up by worms, which can only move fine material.” (Leeper, 1964, 58).

“Mesolithic artifacts dating to beginning of the Holocene are buried to 70–100 cm in Chernozems and 35–60 cm in gray forest soils (Luvisols) of western Ukraine.” (Alexandrovskiy, 2007).

1. Introduction: Dokuchaev vs. Darwin

Although quite different in basic nature and approach, both Darwin's and Dokuchaev's (Fig. 1) contributions to soil science and pedology are, in our opinion, impressive. Despite this, for most of the past century or more, Dokuchaev's contributions have been far more mainstream and widely applied. His theory and model, along with its subtle permutations, have been examined and praised in innumerable textbooks, conferences, symposia, and professional papers. Institutes, awards, medals, official celebrations, museums – and even a crater on Mars – have been named in his honor. Most contemporary soil scientists have been mentored largely under Dokuchaev's (1883) state factor approach, as reinforced and widely popularized at early 20th century International Soil Science Congresses (Bockheim et al., 2014), by giants of the field

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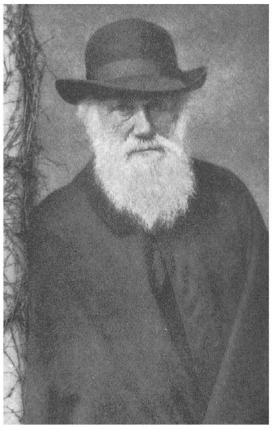


Fig. 1. Left photo of Charles Darwin taken in 1881, the year his soils book was published. Right photo of Vasily Dokuchaev (4th from left, in 2nd row) surrounded by students and colleagues in mid-late career, taken sometime between 1892 and 1895.

like Jenny (1941) and Thorp (1941), in various USDA documents (Soil Survey Staff, 1937, 1951, 1975, 1993, 1999), and as applied in most county soil surveys in the United States (Lindbo et al., 2012; Simonson, 1997). Several popular geomorphological treatises are likewise structured around this approach (Birkeland, 1974, 1984; Retallack, 1990). The longevity of his work has then been extended by his students, colleagues, and Russian peers.

Dokuchaev's body of theoretical work was initially known as the Dokuchaev School of Soil Science, of which his environmental-landscape context scheme formed the central genetic essence (Arnold, 1997; Gennadiev et al., 1996; Jenny, 1941; Thorp, 1941). Although history has given him most of the credit, Dokuchaev's ideas were not conceived independently, e.g., F.A. Fallou and A. Orth already had an understanding of the soil profile as a product of soil-forming factors, A. von Humboldt had described the climatic zonality of vegetation, and E.W. Hilgard had stated that soil distribution depends on climate (Tandarich, 1998). Dokuchaev, however, was able to transform many of these existing views and hypothesis into a logical theory that was useful for predicting soil distributions and formation.

In this approach, **S**oils are explained as a **f**unction of four environmental-landscape (or, state) factors, **cl**imate, **o**rganisms, **r**elief (slope), and **p**arent material, that act over **t**ime, or $\mathbf{S} = \mathbf{f}$ (**cl**, **o**, **r**, **p**, **t** …). Traditionally, the "**o**" factor, disclaimers aside, has had a flora focus, with animals considered as afterthoughts, as minor components, or not at all. Because soils were viewed as a function of these five soil-forming factors, the model has since come to be known as either the functional–factorial model or the state factor model. Its application to explaining soil patterns and genesis is referred to as the factorial approach.

These ideas and this approach were adopted early in Russia, and later elsewhere, as the guiding explanatory paradigm for practitioners not only in soil science, but also in related fields (archeology, ecology, geomorphology, paleopedology, pedology, Quaternary geology, etc.). The model now forms the foundation for discussions of soil formation in many, if not most, of the post-World War II textbooks, especially in North America (Johnson and Hole, 1994; Simonson, 1997). Further, it is the explanatory cornerstone of almost all academic treatises on soils, and is used as the model for soil mapping and survey by the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS). The philosophy even anchors a recent National Science Foundation-National Research Council sponsored white paper that showcases "Earth's Critical Zone" as a framework for integrated studies of 21st century Earth science (Brantley et al., 2006). A 2012 book, sponsored by the Soil Science Society of America (SSSA), that showcases soil science for career-seeking high school and college students also leans on this model (Lindbo et al., 2012). There is no question of the validity or widespread applicability of the factorial model for soil formation. Put plainly, for many applications, it simply works. Alternatively, Darwin's theoretical contributions have centered on processes, not factors. Specifically, he focused on bioturbation.

Darwin may be on record as a groundbreaking evolutionist, but he also was an excellent theoretical pedologist (e.g., Fey, 2010; Humphreys, 1994; Humphreys and Mitchell, 1983; Johnson, 1990; Meysman et al., 2006; Nardi, 2003; Paton et al., 1995; Russell, 1927; Schaetzl and Anderson, 2005; Wilkinson and Humphreys, 2005; Wilkinson et al., 2009; Yarilov, 1936, 1937). And although his ideas have also been discussed, evaluated, and/or used by countless researchers across a number of fields (Atkinson, 1957; Balek, 2002; Dmitriev, 1988; Feller et al., 2001, 2003; Gabet et al., 2014; Ghilarov, 1983; Gould, 1982; Graff, 1983; Hole, 1981; Johnson, 1993a,b, 1994, 1999, 2002; Meysman et al., 2006; Nardi, 2003; Pankov, 1921; Pemberton and Frey, 1990; Stein, 1983; Taylor, 1930, 1935; Wood and Johnson, 1978; Yarilov, 1936), these discussions have not been in mainstream texts or journals. Rather, they are scattered in eclectic venues and hence, have not been widely cited. In short, only a few have worked to extend the longevity of Darwin's work. Even today, many working in the field do not know that Darwin even worked on soil-related problems; he was that "evolution scientist."

Although many in the Earth and allied sciences acknowledge Darwin's (1881) contributions on bioturbation, only a few Eurasian soil specialists, primarily Russian pedologists (Alexandrovskiy, 2003; Anonymous, 1950; Dimo, 1905, 1938, 1955; Dmitriev, 1988; Ghilarov, 1983; Hole, 1981; Pankov, 1921; Russell, 1927; Yarilov, 1936, 1937) have substantively acknowledged or applied it. For example, we have yet to find a single substantive reference to Darwin's work in a USDA- or SSSA-sponsored or inspired soil publication. Likewise, the *comparative contributions* of Darwin and Dokuchaev to soil science have been little developed, beyond those by us and our contemporaries (e.g., Balek, 2002; Johnson, 1993a,b, 1994, 1995, 1999, 2002; Johnson et al., 2005a, 2006b; Schaetzl and Anderson, 2005; Stein, 1983; Van Nest, 2002; Wilkinson et al., 2009).

In this paper, Darwin and Dokuchaev's ideas are developed, but more importantly, compared. Our overarching purpose is to explore the notion that Darwin's contributions to pedology are insufficiently recognized, acknowledged, and utilized. To do this, we must first bring Darwin's academic contributions to greater light; perhaps we owe it to established researchers and educators, and especially to students. We show how Darwin's principles, upgraded in recent decades as biomantle theory, are correct, predictive, and can assist in solving otherwise difficult problems in soil science and geomorphology. We also use this forum to illustrate the subtle but profound role of models and theories in guiding explanatory thought. We then conclude with the opinion that these disciplines are better off when armed with *both* theoretical approaches, as we continue to study the evolution of soils and landscapes.

2. Thumbnail Comparisons and Contrasts of Darwin and Dokuchaev

To provide a historical context for this paper, we first compare and contrast some facts about Darwin and Dokuchaev, their different backgrounds, research timeframes, and even their ages at different points in their respective careers. Some of these data are from Kirianov (1966).

- Darwin and Dokuchaev were born in 1809 and 1846, respectively; they died in 1882 (at age 73) and 1903 (at age 57), respectively.
- Both were university trained, primarily in geology.
- At the time that Dokuchaev was born, Darwin was ~37, had already voyaged around the world, and had published three short papers on experimental process pedology, emphasizing bioturbation.
- Darwin's soil research began in 1837, at age ~28 (after the Beagle voyage), whereas Dokuchaev's began some 40 years later in 1876, at age ~30 (Darwin was then ~67). Thus, Darwin and Dokuchaev were academic contemporaries (though unknowingly to one another) for only ~6 years, from about 1876 to 1882 (when Darwin died).
- The early research and publishing endeavors of both scientists dealt with geological-soil themes, with Darwin's first published paper (1837/1838) being on soil formation.
- Darwin's substantive soil work was *On the Origin of Vegetable Mould, Through the Action of Worms, with Observation on Their Habits*, produced in 1881 at age ~72, was his last publication. (Topsoil in England was then called 'vegetable mould', or 'mould'.)
- Dokuchaev's substantive soil work was his Ph.D. dissertation, published as *Russian Chernozem* in 1883 at age ~37 — near the beginning of his career. He produced many soil-related papers in later years.
- Darwin's book was known during the 20th century more as a worm book than a soils book, whereas Dokuchaev's treatise was always known as a soils book.
- Dokuchaev had many prolific Russian students and disciples, and, later, overseas governmental-academic organizations (USDA, SSSA) to advocate his soil views; Darwin lacked this type of following.
- It appears that Darwin's main research motivation was scientific — to understand and explain why Roman, other historic, and recent surface-deposited objects, became buried. (Notably, though, Darwin also did pioneering research on soil erosion, including the construction of the first rainfall simulator.)
- It appears that Dokuchaev's main motivation was not only scientific, to explain how Chernozems form, but also agronomic and economic — to understand and explain why soils are fertile in some areas, less so in others.
- Darwin was unaware of Dokuchaev's post-1876 soil research (published in Russian and French), although Dokuchaev was aware of Darwin's (1881) book through Lindeman's (1882) Russian translation.
- Dokuchaev's soil model became ruling in the late 19th century Russia, and gained popularity elsewhere during and after the 1930s–1940s.
- Darwin's ideas languished during the 1930s, but were independently re-discovered in the 1975 *Soil Taxonomy*, only to be eliminated from the 1999 version of the same book (Soil Survey Staff, 1975, 1999).
- With the exception of Yarilov (1936), who touted Darwin as the 'father' of soil science, Dokuchaev is viewed as the icon of soil theory; Darwin's historic image is viewed as the icon of evolution and natural selection theory.

3. Dokuchaev on Darwin

Dokuchaev's (1881) *Russian Chernozem*, which was his Ph.D. thesis, only briefly mentioned Darwin's bioturbation work on pages 336 and 337. However, one must read the entire 419 pages of this book to appreciate how brief this snapshot actually was, and the minimal importance he gave to Darwin's work, especially when compared to the work of others he regularly cited, most notably regarding the spatial associations of soils and plant biomes (Fedotova, 2010). His first mention of Darwin's research began on page 336: "The participation of various animals in process of origin of vegetal–terrestrial soil [Chernozem] is somewhat more significant although much less important than assumed by Darwin." His "more significant" point referred to the role animals play in humus formation and soil fertility, not their sorting/mixing roles. Because most Russian Chernozems have formed in thick loess, textural sorting would have necessarily been a non-factor to Dokuchaev. He also discussed the variety of soil fauna (susliks, marmots, worms, etc.) present on the steppes, and summarized his thoughts on the matter as, "All these animals swarm and burrow in the soil and certainly facilitate its comminution and aeration as well as the penetration of organic substances; their activities are naturally conducive to a more uniform distribution of humus and more intense weathering of bedrock." In short, what most impressed Dokuchaev was the role of animals in comminution of raw organic materials and the mixing of the subsequent humus compounds into the mineral soil, and in so doing, aerating the soil. His attention to these processes was for fertility reasons, and to some extent for their role in bedrock weathering. Clearly, those points were apart from Darwin's main message, which was the role of animals in biosorting and creating distinct textural horizons. Such sorting, again, would not have occurred in Chernozems formed in loess. This fact may explain the oversight.

Still, one has to wonder whether Dokuchaev did not grasp Darwin's main points about biomixing and biosorting. Did he understand these processes but simply choose not to emphasize them? Or is it just that they did not apply to the Chernozen landscape? Further reading suggests that he did understand Darwin's ideas, but simply disagreed with them. After stating that "… one cannot agree with such a broad generalization on the part of the famous scientist, even if earthworm activity is supplemented by the activity of other animals …" Dokuchaev gave three reasons (p. 337) why he actually disagreed with Darwin's work. We quote:

1. For nutrition, animals depend on substances in the soil and above it; thus, on dying they add no essentially new substance to the soil. When unusually abundant crops have grown on fields where large masses of different insects have perished previously, it should be borne in mind that this improvement in the soil is only temporary, since it occurred at the expense of humus from the same or neighboring area; the net result in the total economy of soils is negative rather than positive.
2. If one agrees with Darwin that earthworms raise such masses of earth to the surface that flagstones and foundations may be buried, the remarkably gradual decrease in the amount of volatiles and increase in the amount of other substances unchanged upon ignition, observed in the downward direction in all normally situated soils, is not understandable.
3. If all soils have been formed by worms, it is difficult to understand, then, why some soils are black and rich with organic substances [Chernozems] while others are light-gray, low in humus, some thin, about 1/2–1 ft [Podzols] while others are thick, reaching 2–4 ft and more [Chernozems].

Dokuchaev also took issue with Darwin's suggestion that the term "animal layer" might be the better term for soil than "vegetal layer" — an expression then widely used for soil.

What exactly, then, were Darwin's main points? As extolled in his publications (Darwin, 1837, 1840, 1844, 1869, 1881), he observed that animals mix and transfer soil materials, and where soils are gravelly, as his were, they invariably sort them into texturally distinct layers. He wondered why, even when the soil parent material is of mixed grain sizes, A horizons are more or less homogeneous. Thus, in gravelly soils, bioturbation by a dominant bioturbator – worms in Darwin's case – can fundamentally reconfigure and reorganize the particle size character and morphology of the upper- and mid-profiles, leading to texturally distinct horizons.

As noted above, Dokuchaev was more-or-less silent on this matter, mentioning only that animal burrowing facilitates particle comminution, soil aeration, the uniform distribution of organic matter, and facilitates bedrock weathering. Dokuchaev did compliment Darwin for his assessments of the role of animals (in Dokuchaev's view) on soil formation, noting Darwin's "highly ingenious observations, experiments, and calculations" on earthworms in redistributing humus and such. However, in *Russian Chernozem*, Dokuchaev reminded readers of his spatial–factorial approach immediately after discussing Darwin's bioturbation views (p. 338). He also emphasized his factorial approach at the beginning of his book (p. 15), towards its end (p. 379, 382), and elsewhere (p. 297).

Dokuchaev's comments indicate that he was interested in Darwin's work only insomuch as it impacted the redistribution of humus and affected soil fertility; there is no indication that he had an appreciation for the bioturbation/biomechanical aspects of Darwin's work. Hence, Darwin's principal theme, that animals – worms in this case – mix, sort, and thus organize soil into texturally distinct horizons, and in the process cause objects on the surface to drift downward as soil particles are mixed and biotransferred above them, was lost on Dokuchaev. History suggests that Dokuchaev respected Darwin as a scientist and appreciated the soil fertility aspects of his writings, but failed to recognize the biomechanical role of soil fauna.

We return to our question — Why would Dokuchaev *not* have readily endorsed Darwin's animal bioturbation work, in light of his (Dokuchaev's) own vivid and descriptive observations and direct statements of vast numbers of steppe animals that actively bioturbate these soils (cf., Dokuchaev, 1879b, 39; 1883, 239)? Indeed, he even suggested that Chernozems without krotovinas probably do not exist (cf. Dmitriev, 1988). To answer this question, it is useful to place the matter in historical context by examining Dokuchaev's pre-1883 "Chernozem formative years," as they might be called.

In 1876, seven years before *Russian Chernozem* appeared, Dokuchaev began his Ph.D. research. Soon thereafter, he began a series of lectures on Chernozems directed to members of the Free Economic Society of Russia, the scientific organization that sponsored his work, and which would eventually publish some of it (Dokuchaev, 1877, 1878, 1879a). The Society had given him a key "economic" research charge — to determine why some soils were fertile and others were less so, for taxation purposes. This work was to focus on the Chernozem belt, the area with the richest soils. Soil fertility and productivity were, thus, Dokuchaev's main research foci.

During his lectures, which he alternated with library research, writing, and fieldwork, Dokuchaev introduced preliminary versions of his environmental-landscape (factorial) model for explaining the fertility of Chernozems, vis-à-vis the lower fertility of other soils. His comments focused on the more obvious environmental factors that appeared to impact soil fertility on the expansive Ukrainian–Russian steppes, i.e., climate, parent rock, topography, and organisms — and especially steppe plants. As his work progressed, he published updates, advocating his interpretations of how Chernozems develop and become more fertile, eventually producing two summaries of this work (Dokuchaev, 1879b,c). The upshot of this was that, by the time Darwin's Russian-translated book arrived in Russia (Lindeman, 1882), Dokuchaev's *Russian Chernozem* manuscript was being prepared for press, i.e., his worldview of soil factors was likely firmly set. His corpus of pre-1883 writings clearly indicates this. We submit that for these reasons Darwin's animal-soils *process* work did not – and likely could not – resonate with Dokuchaev, even though he well knew and wrote about the effects of burrowing animals on steppe soils, as discussed in his Chernozem volume and in later writings (Dokuchaev, 1892).

Here we provide some additional, historical insight into this matter. Dokuchaev's approach was to search for order in nature, trying to find a model that could predict the "regularities" of an ideal soil pattern. Thus, he did not need any additional factors that made the picture more complex, especially bioturbation. In short, he did not need the bioturbation hypothesis. Another explanation is more personal and a bit more speculative. Dokuchaev had an older, irreconcilable opponent, Pavel Kostychev. Kostychev was a well-known agronomist and a tough person, who blamed Dokuchaev for ignoring the biological factor. Even at the presentation of Dokuchaev's thesis "*Russian Chernozem*," Kostychev publically demanded that the defense of the thesis not be counted. Thus, Dokuchaev may have considered Darwin's publication as a new argument supporting Kostychev.

To summarize, we argue that Darwin's mixing–sorting-biomechanical principles eluded Dokuchaev and were only minimally represented in *Russian Chernozem* because (1) they didn't easily fit into his long-nurtured, environmental-landscape worldview, and/or (2) Darwin's book arrived too late for his ideas to be worked in.

4. Bioturbation Principles and Workings

As distilled from Darwin's work, bioturbation principles imply that animals constantly stir, mix, and transfer soil particles, either directly by tunneling, digging, and scratching, or indirectly, as their tunnels collapse (Fleming et al., 2014). Bioturbationally mixed (and often, sorted) parts or layers in soils are referred to as biomantles. Depending on the particle size characteristics of the original material, a biomantle can be one- or two-layered (Fig. 3). For example, in a uniform, fine-textured material like loess, mixing will often do little to texturally differentiate the soil, and thus, only a one-layer biomantle is formed. Detection, or field-based confirmation, of this biomantle may only be possible by examining the soil fabric or organic matter content. However, if the soil has a mixed particle size suite, including coarse fragments, it can, depending on the *dominant type of bioturbator* (Horwath Burnham et al., 2012), become sorted into two texturally distinct soil horizons. The upper one will typically be a mixed and somewhat homogenized zone, while the one below will commonly be a stonelayer, formed by gravitational settling of clasts too large for the bioturbators to have moved into the zone above (Halfen and Hasiotis, 2010; Johnson, 1990; Figs. 2, 3). Together, these two layers can be considered a biomantle.

The lowermost layer of this two-layered biomantle – the basal stonelayer or stone line – is a genetic soil feature often mistakenly attributed to surficial erosion followed by burial. We acknowledge that buried, erosionally formed, stone lines can appear to be basal stonelayers, and vice-versa. Resolution of the genesis of these types of features in the subsoil is difficult and often fraught with uncertainty, which underscores the importance of this discourse (see Section 8, below).

Figs. 2 and 4 are woodcuts that Darwin and Dokuchaev used in their publications, respectively. Darwin's drawings (Fig. 2) portray the end results of experiments and observations that reflect biomechanical processes. Both capture the unobservable past by summing the effects of small, observable although seemingly trifling, processes, i.e., faunal transfers and sorting. Using updated language, Darwin's profiles are two-layered biomantles (Johnson et al., 2005a). The significance of Dokuchaev's drawings in Fig. 4 is that they portray morphologies typical of Chernozems on the Russian–Ukrainian Plain. Less obvious, but equally important, are myriad visible–subvisible micro-krotovinas and micro-kornevinas in Chernozems and other soils made by rootlets, fungi, and invertebrates (worms, insects, etc.), and smaller life forms. Interestingly, evidence for bioturbation in the form of vertebrate krotovinas is obvious in these woodcuts, but a stonelayer is not, because the loess soils lack coarse fragments. Hence no observable textural reorganization or sorting had (or could have) occurred. [Actually, stonelayers do sometimes occur in loessal soils, but they are often poorly expressed, discontinuous, and composed of avian gastroliths and other allochthonously derived granules, artifacts and manuports (Cox, 1994, 1998; Johnson et al., 2005a,b).] Dokuchaev's profiles are one-layered biomantles (Johnson et al., 2005a; Fig. 3). Because Dokuchaev's

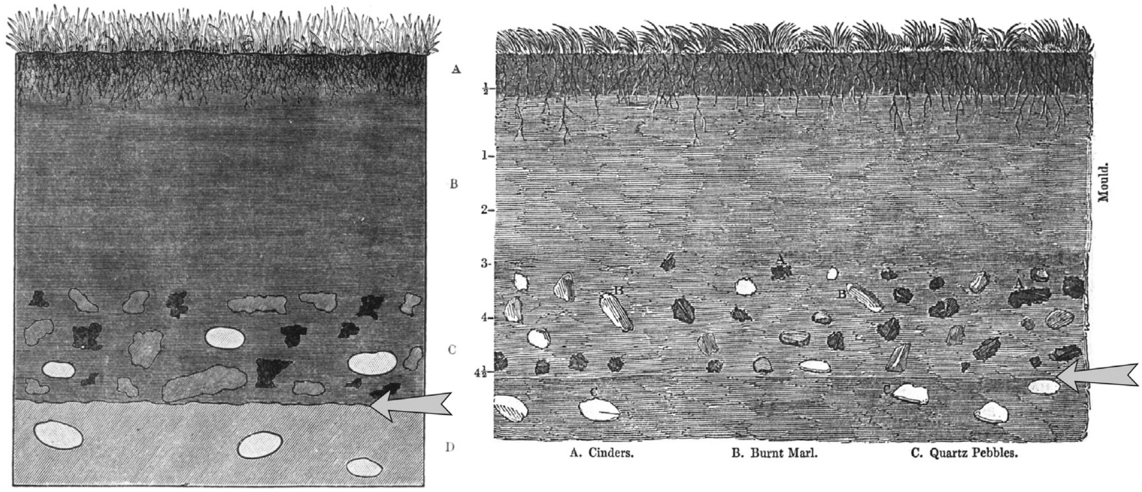

Fig. 2. Two of Darwin's woodcuts, from his 1840 paper (left), and from his 1881 book (right). The flints, cinders, and marl that form the stonelayers (above the arrows) had originally been scattered on the soil surface. Bioturbation by worms and other invertebrates has sorted the materials into two texturally distinct horizons, an upper layer of fines translocated from below and darkened near the surface by humus, above a stonelayer. The material below the arrows (added by us) is the subsoil, above which most bioturbation operated. Although not named as such by him, these images show two-layered biomantles. In England, small invertebrates (worms, mainly) may be the dominant bioturbators.

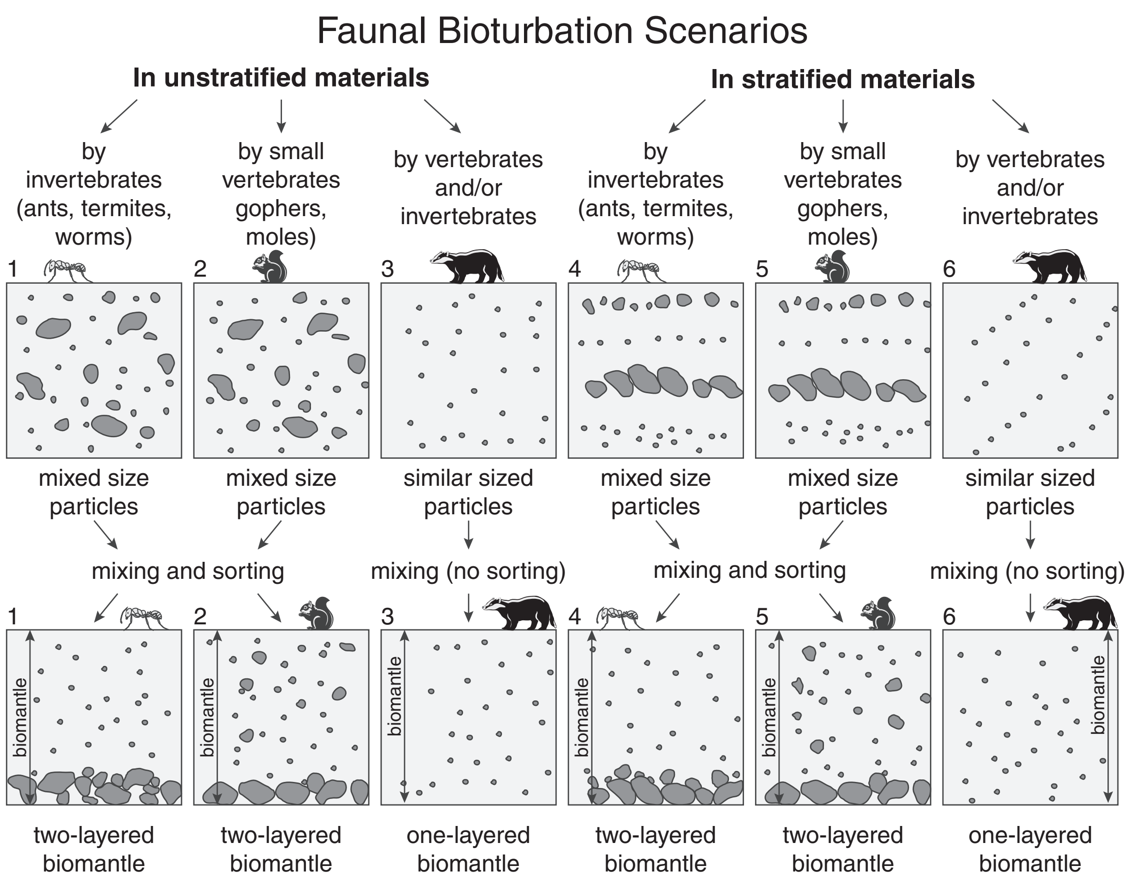

Fig. 3. Illustration of how bioturbation of soil particles by different types of burrowing animals can form one-layered and/or two-layered biomantles. In the top row are the initial parent materials, originally unstratified (columns 1–3) or stratified (columns 4–6). The initial configuration makes no difference to the final biomantle outcomes, as shown in the bottom row. The formation of a one- or two-layered biomantle depends on the particle size characteristics of the sediment and the body size of the dominant bioturbator. If the soil particles are all generally the same size, as with loess or dune sand (top row, column 3 or 6), or as in homogeneous gravels of uniform size that lack fines (not shown), a one-layered biomantle will result, regardless of the bioturbators involved (bottom row, column 3 or 6). In these instances, no size differences in particles exist for animals to sort. Alternatively, if the soil parent material contains particles of mixed sizes, and the dominant bioturbators are small invertebrates (worms, ants, etc.) and/or small vertebrates (pocket gophers, mole-rats, etc.), a two-layered biomantle will form. It will consist of an upper layer of either soil fines (bottom row, column 1 or 4), or uniformly mixed fines and small gravels (bottom row, column 2 or 5), overlying a basal stonelayer (bottom row, column 1, 2, 4, or 5). Particles smaller than the burrow size of the dominant bioturbator are eventually mixed throughout the upper biomantle; particles larger than burrow diameters will settle downward as finer material is removed (biotransferred) from below them, forming a stonelayer at depth.

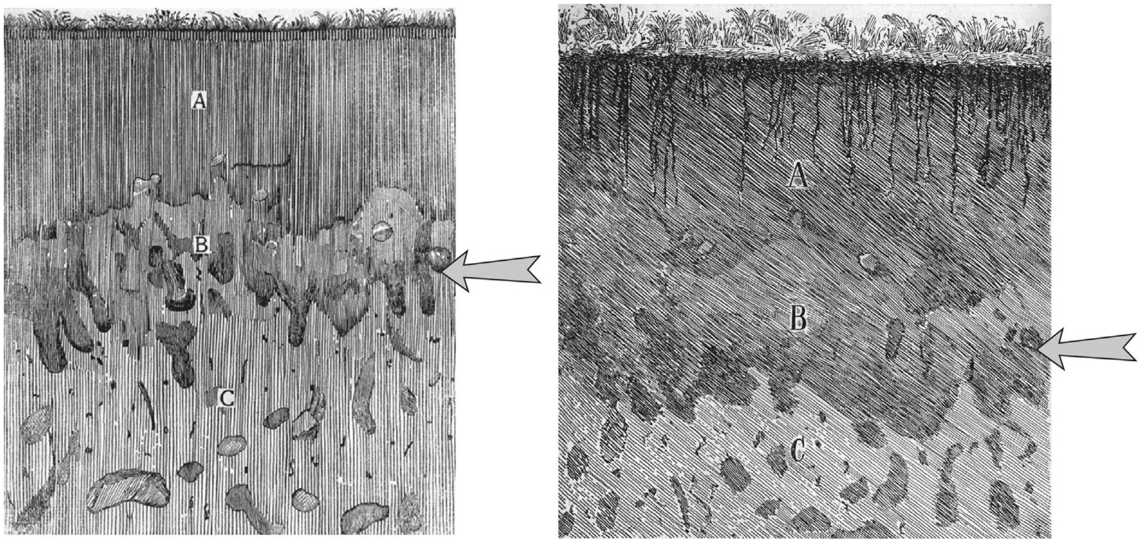

Fig. 4. Two of Dokuchaev's woodcuts: from his 1883 *Russian Chernozem* (left), and from an 1886 publication (right). Krotovinas in the middle and lower profiles in these two woodcuts confirm that bioturbation by small vertebrates had been ongoing in these soils, and that he was aware of their bioturbation. The soil above the arrows (added by us) represents the one-layered biomantle so formed. The upper part of the biomantle is intensely bioturbated but appears more or less homogenized because the uniform dark color renders the krotovinas in it difficult to see (and draw!).

Chernozem soils lacked the stonelayers that are *prima facie* evidence for sorting by bioturbation, and because bioturbation processes were immiscible with the factorial model, Dokuchaev failed to include Darwin's main conceptual point — even though evidence for abundant bioturbation (rodent krotovinas) is present in Dokuchaev's writings (Fig. 4).

Perhaps because Darwin's bioturbation principles were largely missing from *Russian Chernozem*, they also were absent from the mindsets of most later soil scientists who relied on and/or advocated the factorial model as the guiding *sine qua non* paradigm of pedogenesis. This list included most post-1930s, North American USDA personnel and established academics in the field (Johnson and Hole, 1994). These specialists had been intellectually weaned on the explanatory power of the factorial model, as aided by Jenny's (1941) eloquent, follow-up treatise. They, in turn, offered the model to their students as explanatory truth. The knowledge hand-down was not incorrect or inappropriate; it simply lacked bioturbation principles.

Hans Jenny, author of the highly influential book *Factors of Soil Formation* (1941), had apparently at least partly absorbed Dokuchaev's environmental-landscape worldview through the writings of Afanasiev (1927), Glinka (1927), and Marbut (1928, 1935). Thus, Jenny reiterated the factorial model, and with such elegance and simplicity (and with copious supportive data), that it became established as the primary explanatory pedogenic model of the day. Unfortunately, Jenny's book had but one mention (p. 203) of animals as soil formers and/or modifiers: "Because of lack of sufficient observational data covering wide areas, the discussion of animal life is omitted in this treatise." Regardless of this disclaimer, abundant data on bioturbation did exist at the time, albeit from disparate regions covering multiple continents (Formosov, 1928; Grinnell, 1923; Iozefovich, 1928; Johnson, 1990, 1993a,b, 2002; Johnson and Watson-Stegner, 1987; Johnson et al., 2005a,b; Pankov, 1921; Passarge, 1904; Taylor, 1930, 1935). Nonetheless, like many early-mid 20th century soil scientists, it appears that Jenny was generally unaware of Darwin's work.

We use Jenny's book as an example, showing how Darwin's principles were largely overlooked historically, especially within the English-speaking geomorphology and soil science communities—with several recent exceptions (noted below). As a result, bioturbation principles remain largely absent from most basic 20th century soil science treatises and textbooks (e.g., Brady and Weil, 2008; Buol et al., 2011; Lindbo et al., 2012; Soil Survey Staff, 1937, 1951, 1975, 1993, 1999).

5. Mixing Models and the Power of Theoretical Models

If we ask how or why the major players in the soil science community either overlooked or ignored the literature that spotlighted Darwin's bioturbation principles, the answers are likely multiple and complex. They reflect the stochastic and uneven ways in which science develops. We have observed, for example, a pattern where some practitioners cite mainly the mainstream literature of their field, literature that their colleagues cite, usually laden with works by senior gatekeepers. In other words, some researchers appear not to read widely outside their fields, an introverted process that can build on itself over generations and isolate later practitioners from peripheral or non-mainstream ideas, however laudable. This provides one reason why Darwin's work may not have been widely utilized — it simply was not being read.

Another line of reasoning is more theoretical. Philosophically, mixing pedogenic processes with state factors – especially at the time in history when pedogenic theory was still in its infancy – would have been analogous to mixing oil and water. As Simonson (1968) and Johnson (2002) emphasized, such is the power of theory. In short, Dokuchaev viewed soil formation largely through a wide-angled and holistic *soil factors* lens, whereas Darwin viewed soil formation largely through a faunal mixing–sorting–burying, and texturally organizing, *soil process* lens. The differences were so great as to be, conceptually, immiscible.

If our assessment is correct, it portends some important, broader, philosophical issues about theories and models. In short, when a scientific theory, model, or approach becomes mainstream, i.e., it becomes conventional wisdom in a practitioner's mind, that model plays a key role in influencing perceptions and observations, in generating questions, and in influencing decision-making about what is useful or not. Concepts and theories can and do play modulating, mediating, and at times controlling roles in science, which in a sense is partly their purpose. Importantly, the level to which observations and perceptions are modulated and filtered is likely also partly controlled by the inherent agenda of those who employ them. To this point Medawar (1969, 28) reflectively averred that, "Innocent unbiased observation is a myth."

Our essay, this historical example, shows the power of ruling theory in directing subsequent thought, especially if a theory becomes established as conventional wisdom. After attaining such status, a theory or paradigm can marginalize, render unimportant, or even exclude anything not framed or covered within its conceptual domain. Taken to the extreme, scholarly hostility towards competing theories is a not uncommon outgrowth of science. Gould (1984, p. 118) emphasized these points almost as sub-themes in several of his writings.

6. Factors that Worked Against Darwin's Message — Unintended and Otherwise

Several factors worked against Darwin, in the "race" to develop a popular and useful pedogenic model. First of all, Darwin's word choices and communication style, unfortunately and inadvertently, weakened his overall message. For example, with Darwin's international profile as a preeminent life scientist, the title chosen for his book, *On the Origin of Vegetable Mould, Through the Action of Worms, with Observations on Their Habits*, gives the impression that the book is mainly about worms. Had the title consisted of the first six words only, similar to his four earlier soil papers (Darwin, 1837/38, 1840, 1844, 1869), it may have been viewed more as a soils book, and received more attention from soil scientists. Instead, it became largely buried, known mainly to biologists as Darwin's "worm book" (Gould, 1985). In hindsight, this viewpoint was misguided; twice as many chapters (four) are on animal-mediated pedogenic processes and landscape denudation than on worm behavior (two). In recent decades, however, scientists from many disciplines, including archeology, soil science, pedology, ichnology, Earth science, and ecology, have increasingly reclaimed the book as an overlooked, early classic (Atkinson, 1957; Baskin, 2005; Canti, 2003; Clark et al., 2009; Feller et al., 2001, 2003; Ghilarov, 1983; Johnson, 1993a, 1995, 2002; Johnson et al., 2005a; Meysman et al., 2006; Pemberton and Frey, 1990; Tsikalas and Whitesides, 2013; Yarilov, 1936).

A point can also be made in defense of Darwin's emphasis and focus on worm bioturbation per se in soil formation. First, a careful reading shows that although he described worms as key bioturbators in the genesis of soils in England, he also used them as observable analogues for the importance of burrowing animals more generally in soil formation (disclaimers not withstanding — cf. Kinahan, 1882a,b). He mentions, for example, the collective greater role of all burrowing fauna, particularly ants, other insects, larvae, and moles, in pedogenesis. Nonetheless, worms were clearly his favorite, and it was most convenient for him to observe them from his Down House and at other English study sites.

A second factor that weakened Darwin's message was again related to language and word choice. Darwin could not know how terminology might change with time. For example, the terms vegetable mould, mould, and vegetal layer – all 19th century synonyms for topsoil – would be later exclusively replaced by discrete soil horizon terminology such as A and O horizons. Even in the mid 20th century and probably before, the words soil and soil profile carried instant resonance with soil scientists, whereas antiquated terms like vegetable mould and mould simply did not.

Word choice came back to hurt Darwin's message in another way, because he did not coin descriptive and genetic terms (jargon) for the processes about which he wrote. Perhaps if he had, his message would have been strengthened. He chose instead to describe the processes he inferred and experimentally observed in clear, non-technical language, typical of his personal style, and normal for this period in history. Although he expressed it using terms different than the ones used today, the mixing processes and the soil morphologies described above were front-and-center to Darwin's message. It was a consistent message delivered throughout his four decades' investigation of soils, from his first published paper in 1837 (a soil process paper) to his 1881 "worm book." Unfortunately, failure to coin appropriate descriptive and genetic terms can sometimes be deadly in science, even though many scientists (and most laymen) complain about jargon. Defined scientific terms, however, are not only useful, but are also essential for crisp, clear, and exacting communication (Johnson et al., 1997). Notably, terms like *bioturbation*, *biomantle*, *biofabric*, *biotransfers*, *stonelayer*, *faunalturbation*, *floralturbation* and others were all coined long after the Darwin–Dokuchaev era, most in the last 25 years. Perhaps this is why so few of these terms, and the array of concepts they convey, are found in contemporary pedology textbooks.

Another factor that may have diminished Darwin's role and import was his model's focus and perceived narrowness. His model focuses on soil mixing (bioturbation), which is a key *part* of the genesis of many soils, but is not a unifying theme for the genesis of all of them, as was Dokuchaev's factorial model. Darwin's model was never purported to explain the genesis or distribution of all soils, but simply an observation of the importance of one suite of pedogenic processes. Was this observation viewed as trivial by some? Perhaps. But Darwin countered by stating that the maxim de minimis lex non curat [the law is not concerned with trifles] does not apply in science. Later, Gould (1982, 1985) would argue that this maxim echoes one of the key scientific themes embedded in almost all Darwin's writings — that we capture the unobservable past and its processes by summing the effects of the small, observable processes of today. In this case, Darwin observed how slow, sometimes imperceptible bioturbations (trifles) had formed the biodynamic upper part of soil, i.e., its biomantle. Gould (1985, xi) captured Darwin's "trifling" concerns, observations, and notions of small agencies such as worms, ants, and termites, and their accumulated effects, with the aphorism that "Nature's mills, like God's, grind both slowly and exceedingly small." In the end, the soils community did not accept Darwin's model as a wide-reaching and unifying one.

Continuing on with this theme, unlike Dokuchaev, Darwin failed to formulate an easily remembered and teachable *conceptual vehicle* within which to display and frame his ideas and observations, and thus garner support. Scientists and laypersons alike are often attracted to simple and catchy formulations, descriptors and models. Ideally, they should be easily rememberable, or of sound-bite size ($E = mc^2$, Earth's Critical Zone, $S = f[cl, o, r, p, t, \ldots]$, dark matter, plate tectonics, Gaia Hypothesis, etc.). Such formulations, for better or worse, conjure the Occam's razor approach in science, where simpler explanations and concepts are, supposedly, better. Darwin had no such vehicle upon which to carry his message.

In sum, the title of Darwin's book, its perceived focus on worms, his disinclination for coining usefully supportive terms, and his failure to package his theory in an easily remembered and teachable framework, all collectively led to his work being nearly invisible for decades. On the other hand, the agronomic success of Dokuchaev's landscape context (five factors) approach, its simplicity, teachability, wide utility, and ease and simplicity of explanation, from broad landscape to catenary scales, all add up to the reasons for its success.

7. Practicalities of Dokuchaev's and Darwin's Approaches to Soil Formation

Dokuchaev's landscape context model is geographical, factorial, and as designed, agronomic. In it, climate, parent material, topography, age, and plant factors explain the formation and distribution of most soils. The approach has proven invaluable in soil survey and mapping, in studies of soil genesis and classification, for land valuation, and for soil chronosequence work. We do not mean to undermine its utility or importance. Indeed, largely for these reasons, and especially because of the obvious practical agronomic applications, the model established itself early on as the guiding framework for soil research of all kinds. And for most soil scientists, it still is.

To reiterate, Dokuchaev's main research question, prescribed by his sponsors, the Free Economic Society of Russia, was: How can we predict where good agricultural land can be found for mapping, classification, yield, and taxation purposes? By providing answers to these questions in an elegant yet simple and understandable way, the five factors approach became the nucleus of the Dokuchaev School of Soil Science. During and after the 1930s, it also came to form the basis of government-sponsored programs in North America, most notably the USDA, often cooperatively with university programs. By the late 20th century, it had become the theoretical anchor of most soil-geomorphic and soil-climatic research of all kinds (Birkeland, 1974, 1984, 1992; Brye et al., 2004; Gile and Grossman, 1979; Gile et al., 1981; Nettleton et al., 1986; Retallack, 1990; Schaetzl and Isard, 1996).

Conversely, Darwin's approach had far less obvious agronomic and practical applications. It was animal-focused, experimental, and process- (bioturbation-) based. His research was driven by the question: How did cinders and Roman coins end up at depth, when they had originally been on the surface? Fig. 2, drawn from observations at Rothamsted Research Station, aptly captures Darwin's answer. In short, Darwin's soil agenda turned on pure science: to shed light on and resolve an intriguing soil problem, and he spent 40 years at it. Darwin also included organic matter production and soil nutrient supply by organisms – emphasizing worms – in his science and experiments. Aspects of Darwin's field experiments are discussed elsewhere (Canti, 2003; Kieth, 1942; Meysman et al., 2006; Pemberton and Frey, 1990).

Dokuchaev's book had quickly "caught on" with the soil science community; indeed, it may have *created* the soil science community. Conversely, for several decades after its publication, Darwin's book had perhaps registered more impact in other sciences than in soil science (Anonymous, 1901; Bassalik, 1913; Branner, 1896, 1900, 1910; Calvin, 1896; Claypole, 1888; Davison, 1891; Drummond, 1888, 1985; Errera, 1882; Free, 1911; Ghilarov, 1939; Gill, 1883; Gounelle, 1896; Grandeau, 1900; Grinnell, 1923; Haacke, 1886; Henry, 1900; Hensen, 1882; Hughes, 1884; Keilhack, 1899; Kinahan, 1882a,b; Mushketov, 1887; Oriex, 1899; Pankov, 1921; Passarge, 1904; Péringuey, 1911, p. 71; Reid, 1884; Romanes, 1881; Salisbury, 1922, 1924; Seton, 1883, 1904, 1909, 1910; Shaler, 1888, 1891; Stockbridge, 1888; Taylor, 1935; Taylor and McGinnies, 1928; Uruquat, 1883; von Ihering, 1882; cf. Graff, 1983). Indeed, with some notable exceptions (Dimo, 1905; Dmitriev, 1988; Ghilarov, 1983; Russell, 1927; Yarilov, 1936), the book surprisingly had had minimal positive impacts in the very fields that it should have — pedology and soil science.

In sum, Darwin and Dokuchaev's contributions were scientifically lofty and have long proven their utility, although in entirely different ways. We argue that soil practitioners who draw on *both* approaches will significantly increase their explanatory power. But, insofar as five factors theory is time-tested and mainstream, for balance we focus below on Darwin's biomantle concepts, and how their application could have informed considerable soil-related research in the recent past.

8. Biomantle Theory: Helping to Resolve Two Longstanding Soil Geomorphic Questions

Biomantle theory is an expansion and integration of Darwin's bioturbation principles and Thorp's biomantle concept (Johnson, 1989, 1990; Johnson and Watson-Stegner, 1987; Johnson et al., 1987; Soil Survey Staff, 1975, p. 21). It is also a signature component of a broader, theoretical, landscape evolution approach termed *dynamic denudation* (Johnson, 2002; Johnson et al., 2005a,b).

We will demonstrate how biomantle principles can help explain the origin and nature of *stonelayers* and *Mima mounds* — two features whose genesis has long puzzled the academic community. The origins of these features, discussed in Johnson et al. (2005a, p. 20) and Horwath Burnham and Johnson (2012), have garnered a deep and eclectic literature, involving multiple disciplines covering well more than a century. Indeed, one must explore a disparate and sweeping literature to truly appreciate the interdisciplinary breadth, temporal depth, and confusion associated with these two features. For stonelayers, see Johnson et al. (2005a), Johnson (1993a, 2002), and Brammer (1962), especially regarding these features in Africa and Southeast Asia. For Mima mounds, see Washburn (1988), Horwath and Johnson (2006, 2007), Cox and Scheffer (1991), and Horwath Burnham and Johnson (2012). We will show how Darwin's bioturbation model has helped us understand the *processes* associated with each of these features in ways that the factorial model could not.

8.1. Stonelayers

For decades, buried stonelayers have been observed in soils around the globe. Hence, the variety of monikers associate with them is voluminous: stone line, stone zone, pebble band, pebble concentrate, pebble belt, pedisediment, nappe de gravats, a linha de cascalhos, carpetolith, cascalhão, biogenic marker horizon, gravel/stony horizon, nodular layer, boulder line, chert line, quartz émoussés, concentration de quartz, graviers et cailloux, steinlage, basal gravel, basal schotterbändem, graviers et cailloux, colluvion, linea de piedras, ligne de pierres, quartz émoussés, lit de cailloux d'epaisseur, and gravel sheet, among others.

The genesis of stonelayers has been fraught with controversy and confusion (Johnson and Balek, 1991). Process explanations have invoked soil creep (Sharpe, 1938), topographic inversions (Rich, 1953), surficial erosion followed by burial of the erosional stone lag by slopewash or other sediment (Ruhe, 1956, 1959, 1969), surficial erosion followed by burial of the erosional lag by bioturbation (de Heinzelin, 1955), and bioturbation of fines, allowing coarse fragments to sink (Cailleux, 1957; Johnson and Balek, 1991; Taltasse, 1957; Williams, 1968). Other permutations also exist, and usually involve environmental change, which impacts near-surface systems (Alexandre and Malaisse, 1987/1989; Marchesseau, 1965; Twidale, 2006; Vincent, 1966; Vogt, 1966). The controversy was epitomized in a series of 1950s-era notes on stonelayers in South America, Africa, and elsewhere (Cailleux, 1957, 1966; Cailleux and Tricart, 1957; Raynal, 1957; Taltasse, 1957; Tricart, 1957a,b), and more recently in southern Brazil and northeastern Argentina (Humphreys and Adamson, 2000; Iriondo and Kröhling, 1997, 2001; Lichte, 1990; Lichte and Behling, 1999; Morrás et al., 2009). Several of these notes were later translated into Portuguese and extensively re-argued in Brazil (Ab'Sáber, 1965, 1966; Galhego and Espindola, 1980). Papers in the volume by Alexandre and Malaisse (1987/1989) expanded the debate onto other continents.

Stonelayers are particularly common in tropical soils, which typically have complex, highly polygenetic geomorphic histories. Hence, no two of these old, tropical surfaces, technically, ever have similar geomorphic histories. And yet, stonelayers are common to almost all tropical soils formed in residual and transported materials, so long as they contain coarse fragments.

The 20th century literature contains a vast number of papers on "stone line" formation. In almost all of them, the interpretive void left by Darwin's bioturbation principles is obvious, for the explanation for the stone line usually revolves around climatic or erosional–burial scenarios. Thus, many stonelayers have been conventionally interpreted as erosional lags that have subsequently become buried. Commonly, the burial is assumed to have occurred as materials from upslope areas (slopewash) are deposited onto the lag deposits (Kellogg, 1950; Ruhe, 1956, 1959, 1969). However, this scenario cannot be reconciled for flat to convex geomorphic surfaces, and especially on slowly downwasting interfluves (Balek, 2002). Although buried erosional lag deposits do exist on many eroded geomorphic surfaces, especially the older, more complex ones, the genesis of many stone lines is often best explained by bioturbation (Figs. 2, 3).

We propose that bioturbation is the best first explanation for stonelayers in soils that contain coarse fragments, and where bioturbation is or has been present. Under theory like that first proposed by Darwin, soils that bear stonelayers are explained as the lower part of a two-layered biomantle (Johnson, 1990; Fig. 4). Such biomantles are common to all continents except Antarctica. Recent work by ourselves, colleagues, and many others have concluded that most non-imbricated stonelayers within soils are pedogenic (bioturbational) in origin (Figs. 4, 5; Balek, 2002; Horwath, 2002; Humphreys and Adamson, 2000; Johnson, 1990, 1993a, 2002; Johnson and Balek, 1991; Johnson and Watson-Stegner, 1987; Johnson et al., 1987, 2005a,b; Miklos,

Fig. 5. Photo of a two-layered biomantle, approximately 45 cm thick, along Carmel Valley Road, in the Carmel-Monterey area of central California. Whereas worms were the dominant bioturbators that produced the two-layered biomantles in Darwin's tracts (Fig. 2), the dominant bioturbator here, and throughout most of Coastal California, is the pocket gopher *Thomomys bottae*. Photo by Diana Johnson.

1992, 1999; Morrás et al., 2009; Paton et al., 1995; Peacock and Fant, 2002; Quinton, 2001; Van Nest, 2002; Wilkinson and Humphreys, 2005; Wilkinson et al., 2009). A scan of recent literature, however, shows that such features are still often misinterpreted as erosional lags beneath burying sediment (Iriondo and Kröhling, 1997; Lichte, 1990; Lichte and Behling, 1999; Mercader et al., 2003; Twidale, 2006; cf. Humphreys and Adamson, 2000). We argue that, had Darwin's ideas and model been more integral to the overall academic toolkit, this controversy would have been resolved decades ago, and the focus today would be on the nuances of the model, and identifying criteria that can be used to ascertain whether a stonelayer has formed geogenically or biomechanically.

8.2. Mima Mounds

As with stonelayers, the longstanding controversy surrounding Mima mounds (Fig. 6) also can be blamed on the lack of bioturbation principles in the Earth and life sciences. For decades, Mima and other mounds have been mainly attributed to abiotic processes, e.g., erosion, deposition, freeze–thaw, groundwater vortices, gas blows, seismic shaking, human activities, climate change, coppice/eolian accumulations, and/or various combinations thereof (Washburn, 1988). With a few notable exceptions, bioturbation has only infrequently been used to explain the origins of these features. Indeed, the many conflicting hypotheses, summarized by Horwath Burnham and Johnson (2012), joined with dramatic images of Mima Prairie itself (Fig. 6), have stoked the controversy. Kaczorowski and Aronow (1978) lamented: “The debate seems endless!”.

Before the plows of modern agriculture, natural mounds and heaps of all sizes and shapes were a common element of humid midlatitude landscapes, particularly across central-western North America and Eurasia (e.g., Dimo, 1905; Dokuchaev, 1883, 1892; Forshey, 1854; Fowke, 1910; Gilbert, 1875; Houck, 1908; Kalenitchenko, 1860; LeConte, 1874, 1877; Mushketov, 1887; Pallas, 1812; Sviridenko (1927); Webster, 1889; Winchell and Upham, 1881; Wu-Lien-Teh, 1913; Vil'yams, 1949/1968). Mima mounds and moundfields may be similar in gross form, but the mounds themselves vary in size, morphology, density, vegetation cover, texture, etc. Most moundfields of North America are inhabited by small burrowing mammals, mainly by burrowing pocket gophers (*Geomyidae*). Sometimes pocket gophers and ground squirrels (*Sciuridae*), including prairie dogs, inhabit the same moundfield, resulting in significant morphologic complexities. These mounds were, first, constructed by small burrowing mammals and insects, only to be, later, augmented by burrowing predators (badgers, Canids, Mustelids, etc.). In Eurasia, for example, Kalenitchenko (1860), Dokuchaev (1879a), Mushketov (1887), Dimo (1905), and Formosov (1928) reported that astonishing numbers (“millions”) of mounds of burrowing animals (bobak marmots, badgers, canids, ground

Fig. 6. Mima Prairie near Littlerock, Washington, USA. The Northern Pocket Gopher (*Thomomys talpoides*) is the dominant bioturbator that produced this moundfield. Mima Prairie represents a maximal end member on a density-prominence scale of moundfields in North America. Minimal end member prairies have a few low, scattered, and barely discernable rises. Most moundfields lie between these extremes, but towards the minimal end. The man is standing on the basal stonelayer that crops out between the mounds and continues under the mounds; it underlies the entire moundfield. The stonelayer has been subaerially exposed between mounds by the centripetal burrowing styles typical of pocket gophers. This burrowing, and hence, the mounds, are usually only observed where soil is thin above dense substrates, or in periodically wet areas. Mounds are produced during food foraging activities by the gophers. Repeated burrowing outward from their nesting/food storage/activity centers gradually back-transfers soil towards the activity centers. Mima mounds are thus point-centered, locally thickened, two-layered biomantles (Horwath, 2002; Horwath and Johnson, 2006, 2007; Johnson et al., 2002, 2003). Photo by Diana Johnson.

squirrels, hamsters, pole cats, mole rats, ants) dotted the Chernozem steppes of Russia, Ukraine and Trans-Asian deserts into Mongolia and China. Similar "pre-plow" numbers were common for mounds of rodents (prairie dogs, ground squirrels, pocket gophers, kangaroo mice) and ants across central and western North America (Forshey, 1854; Gilbert, 1875; Webster, 1889). Modern Lidar and airphoto coverages confirm that even today, in spite of agriculture and development, millions of mounds remain on these landscapes.

The deep controversy and striking appearance of some moundfields (Fig. 6) have led us to a multi-decadal examination of mounds and moundfields across western North America. Evidence has been slowly and steadily accumulating that Mima mounds are formed by bioturbation, mainly by burrowing rodents, and in the western US, principally by pocket gophers (e.g., Amundson, 1998; Arkley and Brown, 1954; Cox and Scheffer, 1991; Dalquest and Scheffer, 1942; Gilbert, 1875; Horwath, 2002; Horwath Burnham and Johnson, 2012; Horwath and Johnson, 2006, 2007; Irvine, 2005; Johnson et al., 2006a; Koons, 1926, 1948; Price, 1949, 1950; Riefner et al., 2007).

Biomantle theory not only straightforwardly explains Mima and other dominantly faunal-produced mounds in all of these settings, but it consistently predicts the one key attribute of their internal morphologies that human agency or other physical agents cannot (for those mounds formed in gravelly soil) — a basal stonelayer. Wherever Mima mounds form in gravelly soils, they predictably exhibit an upper, locally thickened, zone of fines, i.e., the mound itself (Fig. 5). The fines in the mound are mixed with gravels that are only of a size small enough to fit through burrows made by the dominant burrowers (Cox and Gakahu, 1986; Cox et al., 1987). Gravels in gravelly Mima mounds, particularly when the mounds are made by members of the *Geomyidae* family (40 + species) of rodents (pocket gophers), are invariably less than about 6–7 cm in diameter. The material in the locally thickened mound invariably overlies a basal stonelayer of coarse clasts, as shown in Fig. 3 (boxes 2 and 5, lower row). In other words, Mima mounds are, simply, locally thickened, two-layered biomantles produced dominantly by mammalian bioturbation (Cox and Scheffer, 1991; Johnson et al., 2002, 2003). They form because of the nest-centered, centripetal burrowing style of these rodents (Cox and Allen, 1987; Cox and Scheffer, 1991).

Burrowing mammals are widespread, but mounds are not. Mounds are generally formed where periodic flooding is common, or where a restriction to burrowing exists in the subsurface, either a high water table, bedrock, or a dense and hard soil horizon, i.e., a hardpan of sorts. The animals live where the soil is thickest, or on high, drier ground. On sites where deep burrowing is precluded, mounds are formed as the mammals move soil in the biomantle laterally; the mounds lend a distinct survival advantage to the burrowing fauna (Fig. 6). As a consequence, the mounds get thicker over time and retain a circular shape, except when on slopes, where they elongate in the downslope direction. A stonelayer – found as a basal stonelayer beneath mounds – is also predictably found as a surface pavement in intermound areas, because the finer soil material has been moved laterally, into the mound (Horwath and Johnson, 2006, 2007; Johnson et al., 2006a; cf. Cox and Scheffer, 1991; Dalquest and Scheffer, 1942).

Application of Darwin-type biomantle theory confirms that Mima mounds are neither mysterious nor enigmatic, as has been claimed, but simply locally thickened biomantles produced by highly territorial, burrowing mammals. Where such mounds are formed in gravelly soils they are predictably two-layered, with a basal stonelayer. Where formed in non-gravelly soil they acquire the morphology of locally thickened, one-layered biomantles, and the basal stonelayer is absent.

9. Conclusions

Both Darwin and Dokuchaev made monumental contributions to soil science and pedogenic theory. In most settings, the factorial model of Dokuchaev provides an excellent theoretical framework within which to study and evaluate soil formation and landscape evolution. However, the examples we provide show how it, alone, cannot always provide the necessary framework for explaining all situations and soils. In our discussion, we have emphasized how careful application of the bioturbation principles espoused by Darwin would have led to the solution of two significant and widespread soil-geomorphology questions. For science to advance, explanatory holes in ruling theories must be filled, and Darwin's work does that. Although some have said as much, Darwin's work is not narrowly focused, because his bioturbation principles, upgraded and expanded as biomantle theory, apply broadly.

A careful reading of *Russian Chernozem* makes it clear that Dokuchaev either did not comprehend or simply ignored Darwin's principles. Because of this omission, and that of Jenny (1941) several decades later, a conceptual hole was left in the "o" state factor. This void included many things related to soil fauna, especially the biomechanical processes associated with them. Ironically, not only did abundant morphological evidence for bioturbation in the form of krotovinas and Mima-type mounds exist on the Russian plain, Dokuchaev even cited this evidence in *Russian Chernozem* (Fig. 4) and subsequent writings (Dokuchaev, 1892). Dokuchaev and his contemporaries regularly noted the sausage-shaped krotovinas in the subsoils of Eurasian Chernozems, called "kornevinas" by Sukachev (1902). That said, the reasons he may have ignored Darwin's work were likely two-fold:

(1) The non-gravelly nature of loess-derived Chernozems on which Dokuchaev focused. Except for krotovinas, bioturbation is not overtly obvious in such soils.
(2) The state factor approach he favored coupled with the inherent filtering power of domain-limiting theories. In this case the domain-limiting element was bioturbation, a key soil process in most ecosystems. The five factors model sets the "factorial landscape stage" to explain soils generally, but it is not well designed to shed light on soil mixing or other complex processes.

Like most pedogenic processes, bioturbation occurs in most, if not all, soils. It is a matter of the degree of expression that leads us to attribute the properties of a soil to a certain process or set of processes. In order to develop a complete, accurate and thorough understanding of soils, pedologists must recognize that there are often multiple processes and pathways that lead to similar end results. To that end, both the factorial and biomantle approaches provide different explanatory strengths, interpretive possibilities, and pedogenic utility. They are highly complementary, and that is our point. Each model leads users to different, more diverse and creative ways of unraveling complex pedogenic pathways. Biomantle principles in textbooks have been long needed, were way overdue, and may have finally arrived. Physical geographers, geoarcheologists, pedologists, ecologists, and others can only benefit by drawing on both five factors and biomantle approaches as explanatory tools in reading Earth's complex landscapes.

In retrospect, there are two historical "Masters" of pedology and soil science: Charles Darwin and Vasily Dokuchaev. Darwin's body of scholarship on bioturbation fills a hole in Dokuchaev's "o" factor, leaving contemporary pedologists and soil scientists with a more complete set of tools to understand soil landscape formation. We can learn much about the world from *both* of their legacies.

Dedication

This paper is dedicated to an extraordinary scholar who prematurely left us in 2007, Geoffrey S. Humphreys. In the 1980s–1990s Geoff, with Macquarie University colleagues, effectively (re)introduced the term bioturbation and thereafter a host of related nuances (Humphreys, 1994; Humphreys and Mitchell, 1983, 1988; Humphreys et al., 1996). Thanks, Geoff, for your many creative contributions. Your work lives on.

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