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Concerned with Trifles? A Geophysiological Reading of Charles Darwin's Last Book

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I take shame to myself for not having earlier thanked you for the Diet of Worms, which I have read through with great interest. I must own I had always looked on the worms as amongst the most helpless and unintelligent members of the creation; and am amazed to find that they have a domestic life and public duties! I shall now respect them, even in our Garden Pots; and regard them as something better than food for fishes.
—Sir Joseph Dalton Hooker, Botanist (Letter to Charles Darwin)[1]

Abstract

The last book that Charles Darwin wrote was published one year before his death. It has been celebrated in the fields of soil biology and earthworm ecology as a landmark contribution. Yet outside this specialized literature, there is surprisingly little commentary on what is often referred to as Darwin's "worm book." I argue that the relative neglect of Darwin's worm book stems from his investigating an unorthodox (until recently) topic: the formative impact of organisms on their physical, chemical, and biotic surroundings. I present Darwin's understanding of the global effects of earthworms, and then show that his conceptual and empirical framework is consonant with geophysiology—the science of the Earth as a living system. I conclude with a discussion of the implications of Darwin's argument in the contemporary context of global environmental degradation.

Introduction

The last book that Charles Darwin wrote, *The Formation of Vegetable Mould, Through the Action of Worms, with Observations on Their Habits*, was published in 1881, one year before his death. Often referred to as his "worm book," it has been celebrated in the fields of soil biology and earthworm ecology as a landmark contribution.[2] Darwin introduced its subject matter as "the share that worms have taken in the formation of vegetable mould which covers the whole surface of the land in every moderately humid country" (1985:1). This low-key introduction suggests that the work examines a natural phenomenon of interest only to specialists. Yet the author's insinuation that the topic is narrow and specialized is profoundly misleading. His study examines the enormous impact of earthworm species on the Earth's physical, chemical, geological, and biological environment. Darwin's investigation into how organisms shape their surroundings marks his worm book as pioneering science. Its uniqueness, however, has been somewhat obscured by a misperception of "mould formation by worms" as a phenomenon of limited interest.

Barring its importance in soil biology and earthworm ecology, Darwin's last book has been relatively neglected.[3] The author himself may be partly to blame for this—he was terribly self-conscious that a study of earthworms might be deemed a triviality, and began his manuscript somewhat apologetically: "The subject may appear an insignificant one, but we shall see that it possesses some interest; and the maxim '*de minimis lex non curat*' [the law is not concerned with trifles], does not apply to science" (1985:2). In his typically modest style, Darwin might be paraphrased as saying "I studied the formation of mould by earthworms because trifles are not beneath science." The author's modesty notwithstanding, his last work is far from "concerned with trifles": its main theme—the ways organisms shape, in his words, "the history of the world"—has been a scarce topic of investigation, at least until recently.

Ecologist Paul Ehrlich has remarked that he would not be surprised if a search of "Darwin's work from end to end found that Darwin was prescient about Gaia" (1991:19). In this chapter, I do not contend that Darwin anticipated what James Lovelock would call the "Gaia hypothesis," and yet Ehrlich did hit something of a mark: the argument of Darwin's last work can be read as Gaian or geophysiological. Geophysiology investigates living and nonliving processes on Earth as a coevolving system, within which organisms not only adapt to their environment but also modify it in ways that support their survival and proliferation. I argue that Darwin's presentation of the formidable effects of earthworms on their abiotic and biotic surroundings constitutes a conceptual and empirical approach consonant with present-day geophysiology.

The Formation of Vegetable Mould is a scientific study about the reciprocal influence of life and environment. In investigating this relationship, however, Darwin focused less on earthworms' adaptation to their surroundings, and far more on their significant transformation of the environment. He showed that worms alter the appearance of the landscape; they change the physical texture and chemical composition of the soil; they contribute to disintegration and denudation with subsequent geological-level effects; and their presence or absence is critical with respect to the livelihood of plants. Darwin thus documented the biogeochemical significance of animals that, at first blush, might be dismissed as trivial.

I begin by summarizing Darwin's thesis of the environmental impact of worms; next, I show the affinity between his argument and a geophysiological perspective; I conclude with some thoughts about the environmental implications of his worm book some 120 years after its publication.

The Impact of Worms on the Environment

In constantly upturning and swallowing the soil, earthworms' "chief work," according to Darwin, "is to sift the finer from the coarser particles, to mingle the whole with vegetable debris, and to saturate it with their intestinal secretions" (1985:174–175). Worms turn over, blend, chemically modify, and internally triturate the soil, thereby contributing significantly to its makeup. For nutritive purposes and in the process of burrowing, earthworms swallow earth and then expel it from their bodies as viscid, tower-shaped "castings"—otherwise known as "vegetable mold." (Darwin noted that "the term 'animal mould' would be in some respects more appropriate" [1985:4].) Vegetable mold has passed through worms' bodies countless times, tends to be darker in color from the subsoil, and contains no fragments of stone larger than those that can pass through a worm's alimentary canal (1985:236). Writing to naturalist informants around the world, Darwin inquired whether the formation of vegetable mold is a widespread phenomenon; on the basis of their responses, he deduced that "earthworms are found in all parts of the world, and some of the genera have an enormous range" (1985:120).[4] The author was thus not simply concerned with the work of worms in his own pots, garden, and countryside, but with whether their impact on the soil was a planet-wide phenomenon (1985:128–129).

After establishing the baseline that worms "do much work," Darwin proceeded to measure how much earth they bring up by determining the rate at which surface objects are buried beneath vegetable mold. He discussed numerous cases of natural and man-made objects being eventually buried beneath worm castings, slowly but ceaselessly produced. One description depicts changes in a field near Darwin's house:

> [T]he field was always called by my sons "the stony field." When they ran down the slope the stones clattered together. I remember doubting whether I should live to see these larger flints covered with vegetable mould and turf. But the smaller stones disappeared before many years had elapsed, as did every one of the larger ones after a time; so that after thirty years (1871) a horse could gallop over the compact turf from one end of the field to the other, and not strike a single stone with his shoes. To anyone who remembered the field in 1842, the transformation was wonderful. This was certainly the work of the worms, for though castings were not frequent for several years, yet some were thrown up month after month, and these gradually increased in numbers as the pasture improved. (1985:143–144)

Darwin calculated that the average rate of accumulation was one inch of mold added every dozen years—a steady increase that completely transformed the "now miscalled 'stony field'" (1985:145). All his observations indicated the same trend: the slow and uniform sinking of small and large stones through the action of worms, at rates on average somewhat greater than those determined for the stony field (see 1985:171–172).

Darwin complemented observations of worm-caused changes in landscape appearance with quantitative measurements. He calculated the amount of earth brought up by worms by selecting different terrain types, collecting castings, and weighing them.[5] Different measurements are provided, and four summarized cases yield an average of 14 tons of earth annually ejected per acre (1985:168–169). This impressive amount of earth brought to the surface by worms, and subsequently spread over the land by wind, gravity, and rain, appears less astounding when one considers the "vast number of worms [that] live unseen by us beneath our feet" (1985:158). Citing the calculations of Von Hensen, a German physiologist, Darwin estimated an approximate population of 53,767 worms per acre.[6]

Darwin also documented the impact of earthworms on the landscape by investigating their role in the burial of antiquities (1985:176–229). He examined a number of Roman sites, adducing evidence that ancient objects as well as entire buildings are eventually interred through the slow but relentless work of worms. Through the study of archaeological sites Darwin confirmed how worms change the appearance of the land, and he was also able to determine the depths they inhabit. Excavated areas revealed countless burrows beneath the floors of ruins, indicating that worms can live up to six feet or more inside the earth. Darwin deduced that the burial of ancient buildings is instigated by worms' undermining work below and ultimately is completed by their becoming covered with worm-generated mold above (1985:189–190).

Darwin's study of earthworms' modification of their surroundings culminates in the presentation of geological consequences: worms contribute to "denudation," defined as the removal of "disintegrated matter to a lower level" (1985:231). His argument that worms are a geological force unfolds with an almost deliberate slowness, beginning with a summary of geological findings regarding the disintegration of rocks and denudation. Darwin noted that geologists at first regarded sea waves as the chief agency driving these phenomena, but they eventually included other powerful forces such as rain, streams and rivers, frost, volcanic eruptions, and wind-driven sand (1985:232–235). He reviewed geologists' findings on disintegration and denudation, while also gently exposing how they had been compelled to recognize a larger set of forces at work. He thus set the scene for expanding the list yet again—this time adding the biogeochemical agency of global earthworm activity.

According to Darwin's detailed studies, worms contribute to disintegration in two ways: (1) by virtue of the chemical action of their intestinal secretions and (2) by virtue of the mechanical action of their gizzards on swallowed earth. Soil composition is chemically modified by means of processing organic and inorganic matter in their mildly acidic intestines (1985:240–243). The chemical composition of castings has consistent and cumulative effects, since "the entire mass of the mould over every field passes, in the course of a few years, through their alimentary canals" (1985:243). Castings affect the acidity/alkalinity levels of surface soils as well as deeper layers, contributing to the disintegration of coarse materials, organic debris, and rock fragments. The consequence of these disintegration effects is that the amount and thickness of soil tend to increase (1985:244). Darwin went on to note that "not only do worms aid indirectly in the chemical disintegration of rocks, but there is good reason to believe that they likewise act in a direct and mechanical manner on the smaller particles" (1985:246). Worms have gizzards lined with a coarse membrane and surrounded by muscles that contract forcefully, grinding together, and thus levigating, small particles of earth; the attrition of swallowed materials was supported by Darwin's observation that castings resemble "paint" (1985:249). He concluded this section on the following note: "The trituration of small particles of stone in the gizzards of worms is of more importance *under a geological point of view* than may at first appear to be the case" (1985:257; emphasis added).[7]

After discussing the part worms play in disintegration, Darwin considered how this contributes to "denudation." He found that with rain, worm castings flow down even mildly inclined slopes, while in dry weather they disintegrate into pellets and roll, or are blown, to lower levels. Numerous observations and measurements are given to show that long-term denudation effects are notable. On the basis of eleven sets of observations of the downward flow of castings, coupled with the calculated amount of castings annually brought to the surface, Darwin estimated that each year approximately 2.4 cubic inches of earth cross a horizontal line one yard in length (1985:268). He argued that this amount—a few handfuls of earth—is far from negligible when the inference is drawn with respect to large-scale and long-term effects:

> This amount is small; but we should bear in mind how many branching valleys intersect most countries, the whole length of which must be very great; and that the earth is steadily traveling down both turf-covered sides of each valley. For every 100 yards in length in a valley with sides sloping as in the foregoing cases, 480 cubic inches of damp earth, weighing above 23 pounds, will annually reach the bottom. Here a thick bed of alluvium will accumulate, ready to be washed away in the course of centuries, as the stream in the middle meanders side to side. (1985:269–270)

Darwin's reasoning is at once simple and profound. As Stephen Jay Gould and other scholars have noted, his genius resided in the ability to discern momentous consequences as the cumulative import of small local changes (Gould 1985; Ghilarov 1983). Like his worldview-shattering argument for evolution—as the cumulative upshot of (often) minor variations in organisms over geological time—his panoramic vision of the gradual transformation of a valley over the course of centuries due to earthworm activity reflects his far-reaching insight.

The processing of soil by earthworms is not only significant "under a geological point of view." Throughout the manuscript there are allusions to the vigorous growth of plants and turf in mold-rich regions and, conversely, to the scarcity of plant life where worms are absent. In his conclusion, Darwin tackled the relationship between worms and plants directly. He argued that worms are key for the flourishing of plants, for they "prepare the ground in an excellent manner for the growth of fibrous-rooted plants and for seedlings of all kinds" (1985:309). (He noted that seedlings sometimes germinate when covered with castings—a finding confirmed by recent studies [1985:311].) By burrowing through the earth, bringing up castings and thus replenishing topsoil, and contributing to the disintegration of organic and inorganic materials, worms ceaselessly aerate, blend, and thicken the soil. A soil texture is thereby created that retains and diffuses moisture, and nutritional elements are uniformly distributed and brought closer to the roots of plants.

Darwin captured the intimate affiliation of plants and worms in a beautiful and ecologically astute passage:

> [Worms] mingle the whole intimately together, like a gardener who prepares fine soil for his choicest plants. In this state it is well fitted to retain moisture and to absorb all soluble substances, as well as for the process of nitrification. The bones of dead animals, the harder parts of insects, the shells of land-mollusks, leaves, twigs, &c., are before long all buried beneath the accumulated castings of worms, and are thus brought in a more or less decayed state within reach of the roots of plants. (1985:310)

His ecological view was markedly in contrast to beliefs of his day, when worms were widely believed to be injurious to plant life, and the agricultural and horticultural literature recommended methods to exterminate them (Graff 1983:7). Darwin went on to argue that by benefiting plants, the "gardeners" benefit themselves: as plants flourish, more food for worms is produced—for their main sustenance is leaves and petioles that fall to the ground. In such a biologically rich environment, worms proliferate, thereby increasingly thickening and blending the soil, upon which plants will continue to thrive. Darwin essentially argued that earthworms and plants are connected in a mutually sustaining partnership.

In sum, in his last book Darwin showed that worms have a significant impact on the appearance, chemical constitution, physical structure, geological shaping, and biological organization of the land. By bringing up their castings, earth from deeper layers is continually conducted to the surface; by ceaselessly burrowing, worms mix and aerate the earth; by passing soil through their intestinal tracts, they contribute to the chemical decomposition of earth materials; and by the action of their gizzards, worms directly triturate swallowed matter—including tiny rocks. The compounded consequence of these ongoing worm activities is disintegration of organic matter and small rocks, such that the soil becomes finer and thicker. This contributes to denudation, for there is a tendency for the castings (or "fine earth") to move downward, as well as leeward, through the action of gravity, rain, and wind. Over the course of long time spans, disintegration and denudation facilitated by worms lead to geological-level consequences. Further, as a result of blending and thickening of soil, earthworms support the flourishing of all manner of plants. A thriving plant life, in turn, has significant consequences for both soil and worms: plants counteract the tendency toward denudation by anchoring the soil; and they favor the proliferation of earthworms, for leaves and other plant parts constitute a significant part of worms' diet.

Darwin introduced his inquiry as "the share that worms have taken in the formation of vegetable mould," yet he achieved far more than this low-key statement would suggest: his "worm book" is a pioneering and sophisticated study of the ways that a group of invertebrates interact with, and shape, a broad range of nonliving and living processes of the Earth's land surface.

The Affinity of Darwin's Argument with Geophysiology

Through an interdisciplinary study that is both qualitative and quantitative, that weds geological and biological knowledge, that is empirically rigorous in local inquiry and imaginatively inferential for long-term effects, Darwin demonstrated that something as ostensibly "trite" as vegetable mold is a massive, ceaselessly produced, life-generated, life-enhancing, near-global phenomenon. He painstakingly documented that, far from being inconsequential, earthworms are a significant shaping force of their nonliving and living environment. Nor did he forever shy away from affirming this as the major finding of his study. In the last chapter, the author expressed the scope of his findings with less modesty but far greater accuracy: "Worms," he wrote, "have played a more important part in *the history of the world* than most persons would at first suppose" (1985:305; emphasis added).[8] In this section, I review Darwin's analysis in a geophysiological light. First, a few words about the science of geophysiology.

Geophysiology, or Gaian science, refers to the contemporary scientific inquiry into the biogeochemical dynamics of the Earth.[9] Geophysiology studies the ways that organisms affect and alter their surroundings, and the subsequent repercussions of such life-driven effects for the organisms themselves and for life as a whole. Central to geophysiological thinking are the following working ideas or broadly shared hypotheses: living and nonliving processes are tightly knit—whether systemically coupled or seamlessly continuous; life powerfully modifies (and perhaps even regulates) local, regional, and ultimately global environmental conditions; the adaptive modulation of environmental parameters by living processes constitutes a highly plausible explanation for the resilience of life on Earth for well over 3 billion years; and such a "planetary takeover" by the biota would be favored by (and is consistent with) natural selection, if indeed it has led to the maintenance of key environmental conditions within ranges viable for life as a whole.[10]

Life understood as a planetary phenomenon implicates interdependency and cooperation between organisms in the creation of life-sustaining atmospheric composition, hydrological regimes, and land surface (especially soil) constitution. For geophysiology, air, water, and land environments constitute, metaphorically speaking, the "commons" of the biota: the biota does an impeccable job of preserving those commons—not as static environmental settings but as ever-fluctuating yet always viable surroundings. The commons are not thought to be deliberately maintained, but consist in emergent biogeochemical phenomena such as element cycling, waste use, recycling, decomposition, and regulatory feedback loops—in all of which living organisms, as interdependent players, have the leading role. In studying emergent phenomena that involve intricate connections between life and environment, geophysiology weds the Earth and life sciences. The aim of such interdisciplinary inquiry is to understand the dynamics of the Earth as a living whole.

I now turn to argue that Darwin's understanding of the formidable impact of earthworms on environment is essentially geophysiological. To show this, I rely on a discursive methodology that social scientists have called "rational reconstruction" (see Habermas 1981:197). This methodological approach allows me to explicitly disclaim imputing to Darwin a geophysiological perspective: Gaia was not in Darwin's repertoire, and he might well have disagreed with the present-day geophysiological conception of planet Earth had he encountered it. At the same time, the virtue of reconstructive analysis is that it enables me to demonstrate that the argument of his last book can be conceptualized in geophysiological terms, without distorting or overinterpreting Darwin's own presentation of the impact of earthworms on the land. Using the methodology of rational reconstruction is critical, for I am not claiming that Darwin anticipated the Gaia hypothesis; rather, I am arguing that the thesis of his last book can be read, without strain, as a geophysiological thesis.

Geophysiology emphasizes that organisms play an important role in the creation of their environments. Organisms thereby play an important role in creating themselves, for the environmental conditions they contribute to forming subsequently exert selective pressures on them and their descendants: on straight evolutionary reasoning, it follows that organisms which create a favorable environment for themselves will tend to be selected for through consequent feedback effects from the environment. Darwin's understanding of the shaping force of earthworms on their surroundings resonates strongly with this view: he did not take the land as the given background to which worms adapt, but saw it as a medium actively created and maintained, in large part, by these animals themselves.

In exploring the mutual shaping of life and environment, it has been noted that Darwin's last book is an ecological analysis (see Carson 1994). However, the commentator M. S. Ghilarov has observed that a (subsequently) neglected aspect of ecology was brought to the fore in Darwin's study of earthworms: "Up to a short time ago, ecologists only studied dependence of organisms on their environment." "Darwin," he continues, "has shown brilliantly the other side of the medal—the influence of organisms on their environment, i.e. the dependence of the milieu, of the environment, on their activity" (1983:3–4). Indeed, the other side of the ecological coin—how organisms shape their surroundings—is the main subject matter of geophysiologists, who insist that life does not adjust to "an inert world determined by the dead hand of chemistry and physics" (Lovelock 1988:33). In resonance with this perspective, Darwin showed that worms do more than simply adapt to their surroundings. By producing and tilling the soil, they partake in forming an environment that favors their livelihood. His thesis was thus stronger than the observation that earthworms simply affect the land: he argued that worms transform their environment in ways that contribute to creating a favorable habitat for themselves.

The idea that life and environment shape each other may be regarded as trivially true. However, the geophysiological understanding of the relationship between life and environment as a system (life ↔ environment) is neither trivial nor obviously true. In Darwin's last work, as well, the connection between worms and soil is systemically conceptualized. The ecologist J. E. Satchell, editor of the 1983 collection *Earthworm Ecology: From Darwin to Vermiculture*, writes that "it has always been difficult to formulate a balanced judgement on how far earthworm activity creates fertile soils and how far fertile soils create a favorable environment for earthworm activity" (1983:xi). One hundred years earlier, Darwin was not waylaid by the "chicken-egg" appearance of this matter. He showed that earthworms contribute to the formation and thickening of the soil and simultaneously emphasized that worms prosper in thicker soil. Darwin thus did not conceptualize the relationship between "earthworm activity" ↔ "fertile soils" as a circular formulation in need of resolution, but understood it as a precise description of the phenomenon—which is circular itself.

Indeed, the interaction between earthworms and plants—which is what creates and sustains fertile soils—was essentially described by Darwin as a positive feedback loop: the proliferation of worms and the proliferation of plants are mutually causal, and this two-way causation results in the acceleration of the proliferation of both. The feature of acceleration in positive feedback loops has been a central insight of systems theory—developed decades after Darwin's death. Yet this feature is explicitly put forward in Darwin's observations about the "stony field" (cited above), which, he remarked, became a misnomer after being covered over by mold and turf within a few decades. He observed that "this was certainly the work of the worms, for though castings were not frequent for many years, yet some were thrown up month after month, and *these gradually increased in numbers as the pasture improved*" (1985:143–144; emphasis added). While he provided the average rate of mold increase per year, he emphasized that the actual rate was not constant, but "must have been much slower at first, and afterwards considerably quicker" (1985: 144). The more castings the worms brought up, the more plants grew on the field, the more favorable the environment for worms to thrive: such a feedback mechanism translated into an accelerated rate of mold formation—which increases soil fertility. Fertile soils were thus understood by Darwin as an emergent effect of the tight coupling of earthworms and plant life.

Interestingly, there is also implicit reference in Darwin's work to what would be called a "negative feedback loop" (or homeostasis). Specifically, Darwin noted that through the interplay of living and nonliving processes a relatively stable thickness of vegetable mold is maintained. His reasoning went as follows. Worms tend to increase the thickness of the soil, but this tendency toward ever-increasing thickness is countered by denudation due (especially) to rain and wind; as a result of these inanimate forces, "the superficial mould is prevented from accumulating to a great thickness" (1985:307). Thus, while the layer of vegetable mold that "covers the whole surface of the land" is continually thickened and resifted, it also tends to remain fairly constant. In support of this view, Darwin cited a passage from John Playfair's *Illustrations of the Huttonian Theory of the Earth*: "'In the permanence of a coat of vegetable mould on the surface of the earth,' wrote Playfair in 1802, "we gain a demonstrative proof of the continued destruction of the rocks'" (quoted in Darwin 1985:290).

The remainder of Playfair's passage (not quoted by Darwin) continues without pause: "And cannot but admire the skill, with which the powers of the many chemical and mechanical agents employed in this complicated work, are so adjusted, as to make the supply and the waste of the soil exactly equal to one another" (Playfair 1956:107). Playfair maintained that soil thickness is kept constant by means of ceaseless flux; the "complicated work" of nonliving forces, ever at play, results in "adjustment" or stability. But to the stability of soil conditions achieved somewhat inexplicably, according to Playfair, by "chemical and mechanical agents," Darwin added a truly explanatory biological factor: earthworms. For Darwin, the disintegration effects of worms are integral to the relatively steady constituency and density of the upper layer of the land. Thus he essentially described the attainment of dynamic homeostasis:[11] the incessant activities of worms, combined with the ever-present erosion effects of wind and water, create a steady state of topsoil (see also Gould 1985).

In geophysiological terms, when life plays a key role in creating and sustaining environmental conditions, the process is referred to as a "biological system of regulation" (Lavelle 1996:211). Darwin presented earthworm activity as a biological system of regulation of soil conditions—especially fertility and thickness. Ultimately, worms, organic and inorganic debris, soil, plants, and nonliving forces were understood by Darwin as dynamically integrated—an understanding consonant with a geophysiological perspective. This perspective is expressly interdisciplinary, crossing the boundaries of Earth and life sciences to understand the ways biotic and abiotic processes are enmeshed. "Why run the Earth and life sciences together?" inquires James Lovelock, rhetorically. He responds: "I would ask, why have they been torn apart by the ruthless dissection of science into separate and blinkered disciplines?" (1988:11). Darwin's investigation into the impact of worms on the land draws extensively on Earth and life sciences, producing knowledge that is a contribution from both, but which each alone could never have yielded.

The originality of Darwin's synthesis of geological and biological knowledge hinged especially on his approach to time: by considering the effects of earthworms in extended time frames, he contextualized their living activities in ways that yielded geological insight. Worms were shown to shape the landscape, and ultimately to be a geological force, only by considering their impact over time. The passage of time was variously gauged: in Darwin's observations of the "stony field," for example, the impact of worms was assessed within a human lifetime; in the burial of antiquities, their impact was surmised in terms of centuries; the downward and leeward movement of worm castings was judged considerable "in the course of thousands of years" (1985:289); and consideration of greater time periods—for example, 1 million years—gave insight into the "not insignificant" effects of earthworms:

> Nor should we forget, in considering the power which worms exert in triturating particles of rock, that there is good evidence that on each acre of land ... [that] worms inhabit, a weight of more than ten tons of earth annually passes through their bodies and is brought to the surface. The result for a country the size of Great Britain, within a period not very long in a geological sense, such as a million years, is not insignificant; for the ten tons of earth has to be multiplied first by the above number of years, and then by the numbers of acres fully stocked with worms; and in England, together with Scotland, the land which is cultivated and is well fitted for these animals, has been estimated at 32 million acres. And the product is 320 million tons of earth (1985:258).

The time frame of organisms' life cycles and the time frame of geological events diverge by orders of magnitude. In order, therefore, to discern the geological impact of earthworms, their cumulative effects had to be deductively and inductively extrapolated by Darwin for the long run.

Darwin was impatient with those who could not grasp the significance of the cumulative effects of "a continually recurrent cause" in the course of time. He quoted one critic who remarked about Darwin's conclusions that "considering [worms'] weakness[12] and their size, the work they are represented to accomplish is stupendous" (Darwin 1985:6). Darwin responded with uncharacteristic brusqueness: "Here we have an instance of that inability to sum up the effects of a continually recurrent cause, which has so often retarded the progress of science, as formerly in the case of geology, and more recently in that of the principle of evolution" (1985:6). The influence of a single worm on the environment is obviously negligible, Darwin conceded, but the additive effects, over time, of the widely distributed genera of earthworms—often numbering in thousands of individuals per acre—is, indeed, "stupendous."

It is intriguing that the great evolutionist focused on how earthworms transform the global environment rather than solely exploring the selective pressures that shaped their evolution—as seen in their anatomy, physiology, habits, and adaptive radiation. Natural selection has clearly forged the physical and behavioral characteristics of these animals, and their wide geographic distribution (and 600-million-year presence [Lee 1985]) attests to their success. In his worm book, however, Darwin chose to investigate the other side of the relationship between environment and life—the ways earthworms transform the land and their important role in the history of the world: locally, regionally, and globally, and on timescales from one human lifetime to 1 million years.

Darwin's analysis may be deemed geophysiological on the following counts: (1) the portrayal of the tight coupling of earthworms and land, with particular emphasis on how worms modify their environment; (2) the argument that worms change chemical and physical conditions in ways that are beneficial—rather than neutral or haphazard—to themselves; (3) the implicit description of positive and negative feedback loops that depict systemic connections between worms and their biotic and abiotic environment; (4) the emphasis on earthworms' impact as nearly planetary in scope; and (5) the interdisciplinary character of his study, which joined biological and geological knowledge by extrapolating from local biotic activities to cumulative abiotic effects. In consonance with a geophysiological perspective, Darwin's assessment of the impact of worms essentially agrees with Lovelock's assessment: "The Earth's crust ... [is] either directly the product of living things or else massively modified by their presence" (1988:33).

Gaian literature sometimes cites Darwin's evolutionary perspective as incomplete for missing a geophysiological angle (for example, Lovelock 1988:63). While the geophysiological theme of Darwin's worm book—in which the effects of organisms on their surroundings are emphasized more than their adaptive traits—may not be typical of his work as whole, it is no less significant for this reason.[13] Its significance for Darwin is evident in that his research on earthworms spanned his entire career; as his biographers Adrian Desmond and James Moore write, the book was "forty years in the making" (1992:654).[14] Stephen Jay Gould commented that Charles Darwin is the greatest ally any perspective can claim. On the basis of his last work, I believe geophysiology can rightfully claim Darwin as an antecedent thinker.

Environmental Implications of the Worm Book

The pioneering character of Darwin's last work may be underscored by comparison with the perspective of another great scientist, evolutionary and conservation biologist, E. O. Wilson. In his celebrated essay "The Little Things That Run the World," Wilson presents a generalized version of Darwin's analysis—with the significant addition of implications for a conservation ethic. He draws attention to the role of invertebrates in the preservation of biodiversity by means of a compelling scenario:

> The truth is that we need invertebrates but they don't need us. If human beings were to disappear tomorrow, the world would go on with little change. Gaia, the totality of life on earth, would set about healing itself and return to the rich environmental states of a few thousand years ago. But if invertebrates were to disappear, I doubt that the human species would last more than a few months. Most of the fishes, amphibians, birds, and mammals would crash to extinction about the same time. Next would go the bulk of flowering plants and with them the physical structure of the majority of forests and other terrestrial habitats of the world. The earth would rot. As dead vegetation piled up and dried out, narrowing and closing the channels of nutrient cycles, other complex forms of vegetation would die off, and with them the last remnants of the vertebrates. The remaining fungi, after enjoying a population explosion of stupendous proportions, would also perish. Within a few decades the world would return to the state of a billion years ago, composed primarily of bacteria, algae, and a few other very simple multicellular plants. (1987:345)

Wilson sums up the ecological role of invertebrates in the terse report of what would transpire without them: the earth would rot. In the same vein, a hundred years earlier Darwin averred that "long before [man] existed the land was in fact regularly ploughed, and still continues to be thus ploughed by earthworms" (1985:313).

In her work *Silent Spring*, Rachel Carson was the first to note the significant environmental implications of the worm book. After summarizing Darwin's thesis of the importance of earthworms for the soil—and adding to his observations the crucial role of microorganisms and their connection of earthworms—she wrote: "This soil community, then, consists of a web of interwoven lives, each in some way related to the others—the living creatures depending on the soil, but the soil in turn a vital element of the earth *only so long as this community within it flourishes*" (1994:55–56; emphasis added). More recently, the science journalist Yvonne Baskin referred to the underground community that sustains fertile soils "as a work force, a global service corps of rot and renewal" (1997:108).

Carson observed that "the very nature of the world of soil"—in which the living and nonliving components are inseparably coupled—"has been largely ignored" (1994:57). "Chemical control of insects," she noted, "seems to have proceeded on the assumption that the soil could and would sustain any amount of insult via the introduction of poisons without striking back" (1994:57). As Carson forecast, the soil has struck back: the United Nations Environmental Program reports that since 1945, 300 million hectares of land have been so degraded as to be rendered useless for agriculture (Baskin 1998:107). Agrochemicals are not the sole cause of the global problem of soil ruin; but in killing micro- and macroorganisms that are integral to it, chemicals contribute to dismantling the ecology and undermining the health of the soil. Many agrochemicals are directly toxic to earthworms.[15] The earthworm ecologist K. E. Lee provides an extensive inventory of the effects of various biocides (insecticides, herbicides, fungicides, and fumigants) on earthworms, most of which range from "slightly toxic to very toxic" (1985:292–314).[16]

Biologists have corroborated Darwin's finding that earthworms boost soil fertility, in both arable and wild lands, by maintaining soil structure, aeration, and drainage, and by breaking down organic matter and incorporating it into the earth (e.g., Syers and Springett 1983; Blair et al. 1995). The entomologist C. A. Edwards notes that if soil organic content is maintained, and harmful chemicals are avoided, earthworm populations thrive. "A better understanding of the ecology of earthworms," he adds, "could enable their activities to be manipulated to improve soil fertility" (1983:134–135). Such a biological, age-tested means for creating, enhancing, and tilling the soil—a 600-million-year-old geophysiological technology—was pinpointed with peerless precision by Darwin; yet in the interest of short-term benefits and sky-high profits, soils continue to be treated with abrasive machinery, artificial fertilizers, and toxic chemicals that sooner or later degrade arable lands (see Ehrlich and Ehrlich 1998:243).[17] The impoverishment of soil biodiversity through harsh methods of modern agriculture has been implicated in eventual declines of soil fertility and crop yields (Baskin 1998:113).

Besides their significance for arable lands, earthworms play a critical role in forest soils, especially by preventing the accumulation of leaf litter on forest grounds. In some forest environments, worms consume up to 20 percent of the annual leaf fall—removing organic matter from the surface, breaking it down, enhancing microbial decomposing activity, and thus contributing to the production of humus and the cycling of elements, such as carbon, nitrogen, and phosphorus (see Lee 1985:200–228; Satchell 1983:166–168). Satchell maintains that "in forest soils in which they flourish, earthworms are fundamental to the dynamics of the ecosystem" (1983:168).

Various economic activities damage forests by undermining the soil communities, including the earthworm populations, that support them. Acid rain due to air pollution has had dire effects on forestlands throughout the world—especially in Europe, China, and North America. Acidification kills soil organisms, and is particularly detrimental to earthworms: as a result, forest litter accumulates on the ground, nutrient cycling is retarded, and the aboveground ecosystem eventually suffers (Ehrlich and Ehrlich 1998:148).[18] Moreover, clear-cutting is not only (obviously) detrimental to the aboveground forest flora and fauna, but also to the underground ecosystem vital for a forest's sustenance. Attempts to get new seedlings started on clear-cuts often fail for decades, because the ecological infrastructure of the soil has been undermined beyond viability thresholds—whether by overly efficient vegetation removal, logging skids, or application of fumigants and herbicides (ironically) to assist replanting (Baskin 1998:117).

The chemist M. H. B. Hayes notes that to this day there is insufficient awareness of the importance of earthworms, even though research clearly indicates that soil structure is invariably good when an adequate earthworm population is present (1983:28–29).[19] Darwin's prescience is all the more remarkable when one considers that the constructive role of earthworms for the land continues to be ignored or underestimated—even in the present, when topsoil erosion, soil degradation, and forest declines are widely acknowledged as critical ecological problems.

In the roughly 120 years that have elapsed since its publication, Darwin's last work has proven to be both pathbreaking and current. Contemporary soil and earthworm ecologists have confirmed the accuracy of Darwin's findings regarding the important contribution of worms to the nature of the land. His understanding embedded an ecological perspective and systems thinking decades before the respective fields emerged. If the analysis of this chapter is correct, in his last work Darwin also anticipated key elements of geophysiological science almost a century before its inauguration with the work of James Lovelock and Lynn Margulis. Finally, Darwin's understanding of the ecological role of earthworms speaks to the plight of cultivated and forest lands, and is profoundly current in its conservation implications. As Stephen Kellert has so aptly noted, to reverse the "trend toward the increasing impoverishment of the planet's biological diversity, we will need to acquire a more appreciative attitude toward the biological matrix of so-called 'lower' life forms represented by the invertebrates" (1993:852).

Conclusion

I suggest that the significance of Darwin's last work has been largely overlooked because its interdisciplinary, arguably geophysiological perspective has been incongruent with disciplinary and specialization trends in science. Add to this that in his study of their habits, Darwin argued that earthworms show "some degree of intelligence"—an apparently embarrassing idea for much subsequent behavioral science (see Crist 2002). The fate of the worm book was further sealed by a common human propensity to belittle and even despise invertebrates (Kellert 1993). In these ways, *The Formation of Vegetable Mould, Through the Action of Worms with Observations on Their Habits* has been, to use a colloquialism, "outside the box."

Perhaps it is not hyperbolic to say that the force of this work drives a punch that has made it difficult to acknowledge without disturbing scientific and commonsense orthodoxies. The author of the worm book was not known to abide by either.

Charles Darwin did not study worms because he was an inveterate naturalist who enjoyed tinkering with the soil—although he was that, too. Darwin was not above studying simple organisms like earthworms because his scientific vision was unusually lucid: he was able to unearth the deep knowledge that life safeguards in the most unsuspected recesses of its universe.

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Notes

1. Cited in Porter 1988:8.

2. It has been key in the understanding of "pedogenesis"—the study of the formation and development of soil. In an edited collection of papers on contemporary developments in earthworm ecology, J. E. Satchell notes that "Darwin's views on earthworm pedogenesis have been fully vindicated" (1983:xi–xii). See also K. E. Lee (1985). On the overall positive reception of Darwin's last book, including reviews in his own day, see Graff (1983). For a review of the 1985 edition of the work, see Porter (1988).

3. Exceptions are Yerkes (1912), Ghiselin (1969), Graff (1983), and Gould (1983, 1985).

4. While Darwin's claim that earthworms "have an enormous range" has proven correct, his wording that they are "found in all parts of the world" is somewhat overstated. Elsewhere in the book, he gives a more accurate portrayal of worms found in "all humid, even moderately humid, countries" (1985:235–236). According to the soil biologist K. E. Lee, "in tropical and temperate regions alike earthworms are among the most widespread of invertebrate animals and are found mainly in the soils of forests, woodlands, shrublands and grasslands, which together cover ... *ca.* 54 percent of the land surface of the earth (1985:179). The ecological function that Darwin attributed to earthworms—that they "plough the land" (1985:313)—has since been both corroborated and made more accurate, by generalizing this role to include all invertebrates and associated microbial groups of the Earth's surface (see Wilson 1987; Lavelle 1996).

5. For these measurements, Darwin relied in part on the help of "a lady on whose accuracy I can implicitly rely" (1985:165).

6. Commenting on this estimate, he wrote that "the above result, astonishing though it may be, seems to me credible, judging from the number of worms that I have sometimes seen, and the number daily destroyed by birds without the species being exterminated" (1985:159). On the close collaboration via correspondence between Darwin and Hensen, see Graff (1983).

7. Worms' triturating effects are mostly significant, Darwin emphasized, at very fine levels of particles—no bigger than can pass through their alimentary canals. Their impact on a diminutive scale is all the more crucial for that very reason: on this scale, agencies like running water or ocean waves have negligible effects, acting "with less and less power on fragments of rock the smaller they are" (1985:257).

8. In the last paragraph of the book, Darwin reiterated his conclusion that worms have played an "important part in the history of the world" (313); by using the expression "history of the world" twice, he indicated that he meant it seriously and not as an offhand turn of phrase.

9. As a terminological caveat, I note parenthetically that I am partial to the term "geophysiology" over "Gaian science." "Gaia" (the "G word," as Lynn Margulis puts it) produces strong reactions among different constituencies in ways that often divert from the substance of the science. On the other hand, the concept "geophysiology" has the virtues of carrying no distracting extrascientific implications, being general enough to include a longer history, and precise enough to capture the idea of the Earth as a living system.

10. On the Gaia hypothesis and Gaian science, see Lovelock (1979, 1987a, 1987b, 1988, 2002); Margulis and Lovelock (1974); Margulis (1981, 1987, 1996, 1998); Margulis and Sagan (1997); Volk (1998). Edited collections on Gaia include Schneider and Boston (1991); Bunyard (1996); Barlow (1991); and Thompson (1987). A good introduction to the history and idea of Gaia is Joseph (1990).

11. The idea of homeostasis has been central in present-day geophysiology: it is defined as the maintenance of conditions by active biotic control, indicating the Earth system's capacity to sustain a range of chemical and physical parameters viable for life as a whole. Darwin's citation of Playfair is interesting for forming an indirect link to contemporary geophysiology. Playfair was a proponent of James Hutton's geological views, and Hutton has been cited as a precursor of the geophysiological perspective. At the 1785 meeting of the Royal Society of Edinburgh, Hutton maintained "that the Earth was a living organism and that its proper study should be geophysiology" (quoted in Lovelock 1988:10).

12. From his observations of worm burrowing, and of the depths they are capable of penetrating, Darwin deduced that worms possess great "muscular power" (1985:188). This is corroborated by recent findings regarding the high protein constitution of earthworms.

13. Darwin's first book, *The Structure & Distribution of Coral Reefs*, in which he describes the different types of coral reefs and explains the origin of their peculiar forms, was also concerned with the geological-level effects of life—in this case, of marine organisms. Darwin was aware of the connection between the themes of his first and last books, and ended *The Formation of Vegetable Mould* as follows: "Some other animals ... still more lowly organized [than earthworms], namely corals, have done far more conspicuous work in having constructed innumerable reefs and islands in the great oceans; but these are almost confined to the tropical zones" (1985:313). See Ghiselin (1984).

14. Prior to the 1881 publication of *The Formation of Vegetable Mould*, Darwin published three papers on the formation mold by worms (in 1837, 1844, and 1869). These papers are reprinted in *The Collected Papers of Charles Darwin*, edited by Paul H. Barrett.

15. Toxic chemicals also adversely affect wildlife by entering the food chain through the worms. Earthworms are composed mostly of protein and therefore are highly nutritious. They are prey for a number of animals, including some amphibians, reptiles, birds (even raptors such as owls and kestrels), and mammals (for example, moles, raccoons, foxes, and badgers) (Macdonald 1983).

16. On the other hand, Edwards et al. note that earthworm populations rise as agriculture moves away from fertilizers and biocides, relying instead on organic methods of rotation and biological sources of fertility and pest control. They predict that the role of earthworms for productivity will become increasingly prominent as trends favoring organic farming continue (1995:186).

17. Plowing destroys worms by digging them up and making them available to predators—especially birds.

18. Environmental analyst Charles E. Little notes that "on the forest floor in the Middle West, and presumably elsewhere, the earthworms are dying" (1997:229). Citing the ecologist Orie Loucks, he writes that parts of Ohio and Indiana subject to acid rain show a 97 percent decline in the density of earthworms (1997: 229).

19. Organic farming, or agroecology, constitutes the exception: the utilization of worms to enhance the nutritional value, and structural efficacy, of soils is known as vermiculture.

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