ECOLOGY

Earthworms' place on Earth

A new study provides a global view of earthworm ecology

By **Noah Fierer**

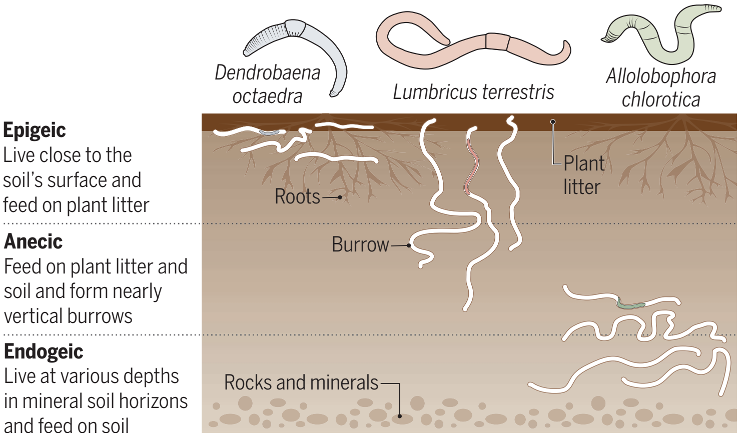
After revolutionizing our understanding of life on Earth, Charles Darwin studied earthworms. In 1881, he published his last scientific book, a treatise on earthworms (*1*) whose sales at the time rivaled those of *On the Origin of Species*. Nearly 140 years later, enthusiasm for earthworms persists, fueled by the recognition of their importance in terrestrial systems as different as backyards and tropical rainforests. On page 480 of this issue, Phillips *et al.* document an impressive group effort by 141 researchers from 35 countries to develop a global-scale atlas of earthworms (*2*). Darwin's legacy continues.

Earthworms, as ecosystem engineers by nature (*3*), influence the structure and functioning of terrestrial ecosystems. Through their burrowing activities, earthworms promote the stabilization of soil particles into aggregates, increase soil porosity, and elevate the rates at which water infiltrates soil during rainfall; reduce erosion of surface soils from hillslopes; and accelerate the movement of gases into or out of soil. Referred to by Aristotle as Earth's intestines, earthworms accelerate organic matter decomposition by ingesting more than 30 times their own weight in soil per day and can rapidly mix large amounts of leaf litter into underlying soil horizons, increasing the release of plant nutrients. The presence of earthworms typically enhances plant growth, including that of most crops, but the magnitude of this effect varies depending on the plant and earthworm species in question (*4*).

A striking example of the impact that earthworms can have on ecosystems comes from studies of temperate and boreal forests that were left devoid of earthworms after the last glacial period. As these earthworm-free ecosystems became colonized by exotic earthworm species, the forests quickly lost the thick litter layers blanketing the soil surface, with corresponding shifts in soil carbon and nitrogen dynamics (*5*). Earthworm invasion can, in turn, cause drastic shifts in plant communities, often leading to the replacement of diverse understory herbaceous and tree seedling communities with lower-diversity plant communities (*6*).

Earthworm ecology

Shown are three main ecological categories of earthworms and examples of resident earthworm species. Not all species fall neatly into these categories, as some earthworms can vary their burrowing and feeding preferences depending on life stage and soil conditions.



Earthworms are found in both managed and unmanaged soils worldwide and can be surprisingly abundant. A single square meter can contain more than 150 individual earthworms with a collective biomass that can exceed 1500 kg per hectare (roughly equivalent to the weight of two adult cattle). Earthworms are also highly diverse, with at least 7000 described species and many more likely awaiting description. Their taxonomic diversity is matched by their morphological and ecological diversity. Earthworms can range in length from just a few centimeters to 3 m (e.g., the endangered *Megascolides australis*) and can be grouped into general categories on the basis of their feeding preferences and burrow architectures, which contribute to species-specific effects on soil properties (see the figure) (*7*).

Despite their clear importance in terrestrial ecosystems, there have been surprisingly few attempts to describe the global biogeographical patterns of earthworms. Unlike many aboveground plant and animal taxa that have been studied at the global scale for decades, ecologists have had only an anecdotal understanding of how the diversity and abundances of earthworms vary on Earth. The Phillips *et al.* study takes an important step toward addressing this knowledge gap.

The authors surveyed ~7000 sites in 56 countries and documented a variety of earthworm distribution patterns. Some were in line with expectations garnered from the way aboveground taxa commonly are distributed on Earth. For example, climatic variables (namely precipitation and temperature) were the best predictors of earthworm diversity and biomass, which is also true for many aboveground taxa. However, other earthworm patterns contrasted with preexisting paradigms in the field of biogeography. For example, unlike many plant and animal taxa (*8*), the diversity of earthworms is not necessarily highest in lower-latitude tropical systems. Southern England might not be considered a hotspot of plant or animal diversity, but it is a veritable earthworm paradise, with soils harboring some of the highest diversity and abundances of earthworms.

Scientific studies are also just as useful for informing researchers of what they don't know. When it comes to earthworms, data show that there is a clear need for more investigations of diversity in particular regions. Although tropical soils appear to have lower earthworm diversity than higher-latitude soils and a greater degree of endemism (i.e., few taxa shared across sites), this pattern might be a product of the paucity of earthworm biologists working in tropical regions. In addition, although the work by Phillips *et al.* demonstrates that earthworm distributions are highly sensitive to climate, it remains unclear how earthworms in soils across the globe will respond to ongoing climate change and what such responses might mean for the functioning of terrestrial ecosystems. Likewise, the local-scale impacts of land-use changes (including pesticide use, tilling, and other agricultural practices) were not the focus of the new study, although ecologists know that such disturbances can

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profoundly alter earthworm populations (*9*). Given the role of earthworms as ecosystem engineers, changes in their diversity and distributions clearly warrant further investigation. Phillips *et al.* provide a roadmap to guide such investigations.

The new study also adds to ongoing efforts to document the diversity of other soil organisms, including bacteria (*10*), fungi (*11*), and nematodes (*12*). These studies are fueled, in part, by the increasing recognition that soil biodiversity is of under-recognized importance to human and ecosystem health. For these reasons, the Global Soil Biodiversity Initiative (*13*) is leading international efforts to gather the scientific knowledge needed to guide and promote the conservation of soil biodiversity. Because soil communities are not necessarily mirror images of aboveground

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communities, conservation policies designed to protect the more visible aboveground plants and animals might fail to adequately protect the biological diversity hidden beneath our feet. To know how to maximize crop production in agroecosystems, sequester more carbon in soil, or to understand how terrestrial ecosystems will shift in response to human activities, ecologists must learn which soil organisms live where, and what functions they serve in their respective ecosystems. Otherwise, we might not recognize what has been lost before it is too late. ■

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BATTERIES

How lithium dendrites form in liquid batteries

Studies of interfacial reactions and mass transport may allow safe use of lithium metal anodes

By **Jie Xiao**

Conventional rechargeable lithium (Li)–ion batteries generally use graphite as the anode, where Li ions are stored in the layered graphite. However, the use of Li metal as the anode is now being reconsidered. These next-generation battery technologies could potentially double the cell energy of conventional Li-ion batteries (*1*). Rechargeable Li metal batteries were commercialized more than four decades ago but were in use only briefly because of safety concerns (*2*). With the advancements of electrolyte (*3*, *4*), electrode architecture (*5*), and characterization techniques (*6*) in recent years, a better fundamental understanding of the interfacial reactions during charging and discharging that dictate cell performance has developed and inspired a reevaluation of the use of Li metal anodes in rechargeable batteries.

The main challenge of Li metal cells is that during charging, the Li metal electrochemically plates in an irregular manner, forming spiky microstructures, like other metals electroplated from solution, in the absence of "levelers" or "brighteners." Without these added organic compounds, whose presence results in a smoother, brighter metal surface, the metals are always dendritic or powdery (*7*). Metal dendrite formation is rooted in the mass transport of the metal cations, which are surrounded by solvent molecules and must move from bulk electrolyte to the outer limit of the electrical double layer near the electrode, followed by electro-adsorption. The solvated cations then shed the solvent molecules and are reduced into adsorbed atoms (adatoms) on the electrode surface. These adatoms diffuse on the surface and become incorporated by the metal lattice.

Mass transfer of metal cations in the electrolyte phase largely determines the final morphologies of electroplated metals, even if this process is often ignored in discussions of Li dendrite formation. Three forms of mass transport affect the cations in solution, namely diffusion, convection, and migration (see the figure). During electroreduction, the direction of cation diffusion aligns with their electromigration pathway. However, natural convection is unavoidable and unpredictable even in a static electrochemical cell (one with no net flow) and interferes with this process. Thus, some cations will move faster or slower than others, which creates different concentration gradients near the electrode (see the figure, top).

Assuming that the electrochemical deposition rate of cations is not very fast and stays the same throughout the entire electrode and that there is no interface layer formed between electrode and liquid electrolyte, a very slow movement of cations to the electrode surface can make the concentration gradient even steeper because cations are not fully replenished immediately after electroplating (see the figure, middle). Metal dendrites propagate into bulk electrolyte where more cations are available. The metal protrusion also experiences higher current densities, which self-accelerates the dendrite to grow.

If the cations move very fast in the electrolyte, the concentration gradient near the electrode is shallower (see the figure, bottom), and the metal has no preferred growth direction. Relatively large particles without sharp protrusion are usually formed when mass transport is not a concern. Once an electroplated metal particle becomes sufficiently large, it acts as a new current collector that can grow its own dendrites on the surface (*8*). The observation of randomly formed fibrous Li extending out from a Li particle reflects the different convection conditions within that area during Li plating. When a high current density is applied, electrochemical reduction or the consumption rate of Li ions is largely accelerated. Thus, the diffusion rate of Li ions in the electrolyte becomes relatively slower compared to their rate of being consumed. Strong concentration gradients are easily established throughout the entire electrode, so the metal deposition is usually highly inhomogeneous at high current densities.

Because Li metal reacts with the organic solvent of the electrolyte, the decomposition products form solid-electrolyte interphase (SEI) layers, and the higher surface areas of dendritic Li are even more reactive.

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