about its structure. This unsupervised, graph-based algorithm orders the waveforms to minimize dissimilarities and can reveal trends without an Earth model. The analysis by Kim *et al.* detected subtle changes in seismic waveforms from earthquakes that occurred in Asia and Oceania and were recorded in the Americas and mapped their origins across a large geographic region beneath the Pacific Ocean.

The new study also identified more broadly distributed ULVZs at the base of the mantle north of Hawaii and a previously undetected anomaly in the deepest

"... a manifold algorithm... enabled a data-driven analysis of the deep mantle without any expectations or prior knowledge about its structure."

mantle beneath the south-central Pacific. This type of analysis could be applied to various seismic phases such as *ScS*, *ScP*, and P_{diff} and a range of others that are of higher frequency, which would provide a new, higher-resolution, and more comprehensive mapping of the structural heterogeneity of deep Earth. Knowledge of these physical properties and of inferred chemical and thermal structures is essential to determining whether partial melt of the rocks exists at the core-mantle boundary, whether distinct materials accumulate or stabilize in particular regions, whether some volcanoes have origins in deep Earth, and, last, what the compositional variations are in the lowermost mantle. ■

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ECOLOGY

The global odyssey of plastic pollution

Thinking big about small particles reveals new features of the microplastic cycle

By **Chelsea M. Rochman**[1] *and* **Timothy Hoellein**[2]

Scientists who once studied microplastics (plastic debris <5 mm in size) as ocean pollutants have now detected them in soils, biota, and Earth's atmosphere. To decipher the global fate of microplastics, scientists have begun to ask questions about the "microplastic cycle," which is akin to global biogeochemical cycles (nitrogen, carbon, and water). For example, what are the sources of microplastics, and how do they transform as they move from one pool (e.g., a beach, inside an organism, or a river bed) to another? And what processes ("fluxes") transfer microplastics between pools? On page 1257 of this issue, Brahney *et al.* (*1*) report high-resolution spatial and temporal data that provide evidence of both global and regional microplastic transport, thus increasing our understanding of the microplastic cycle.

Nearly a decade ago, scientists began studying marine microplastics in surface currents of the ocean as the key mechanism for global transport. As datasets grew, their understanding of long-range transport within and between oceans expanded to include mechanisms such as deep-sea circulation (*2*), biological transport (*3*, *4*), and drifting sea ice (*5*). In parallel, emerging work uncovered pools of microplastics in other Earth compartments, including freshwater and terrestrial systems (*6*), and the atmosphere (*7*). To fully understand the microplastic cycle, researchers must piece together the fluxes that connect the transport and transformation of microplastics as they move between planetary compartments.

Atmospheric transport of microplastics in airborne dust, which settles to the ground (deposition) during dry and wet periods and in both urban and remote locations, was initially overlooked. Scientists have understood the global transport of dust for decades, but until recently, dust was not known to carry substantial amounts of microplastics. Seminal work on transport of microplastics in the atmosphere demonstrated their presence in wet (e.g., rain, snow) and dry deposition in Paris, France (*8*), providing proof that microplastics are a component of dust and that atmospheric deposition is a mechanism of transport. Long-range atmospheric transport, away from urban centers, was first demonstrated in 2019, when microplastics were unearthed from a remote mountain catchment (*7*) and in Arctic snow (*9*). These studies prove that microplastics are transported atmospherically to both regional and faraway places.

Brahney *et al.* studied both global and regional transport of microplastics by comparing the size and shape of particles deposited in dry and wet weather (see the figure). The new work elucidates patterns of deposition and processes of atmospheric transport, and predicts that atmospheric transport is an important source of microplastics in remote locations. For example, the authors estimate that more than 122 tons of microplastics are deposited annually to U.S. protected lands of the western United States.

By incorporating human population metrics, local weather patterns, and climate models, Brahney *et al.* found that larger microplastics were deposited during wet events and likely originated from nearby urban centers during regional storms. In contrast, smaller microplastics deposited during dry weather were more likely to have been transported long distances and made up the majority of the microplastic mass.

A key insight from the new work is that fundamental tools for studying global dust transport can be applied to microplastics. Like dust, most particles measured were within the size range typical of global transport (<25 µm). However, microplastics are less dense than soil and therefore might travel longer distances than natural dust particles. Future research should test hypotheses about the distances that microplastics can travel atmospherically and the processes that entrain microplastics in the air, such as sea spray and dust storms. The new study also invites questions about latitudinal gradients. Global atmospheric circulation is affected, in part, by air rising at 0° and 60° latitude and

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sinking at 30° and 90°. Do researchers expect movement of atmospheric microplastics to follow similar patterns? Moreover, scientists know that dust particles are a vector for atmospheric distribution of chemical contaminants and microbes. How do microplastics interfere or aid in such spread?

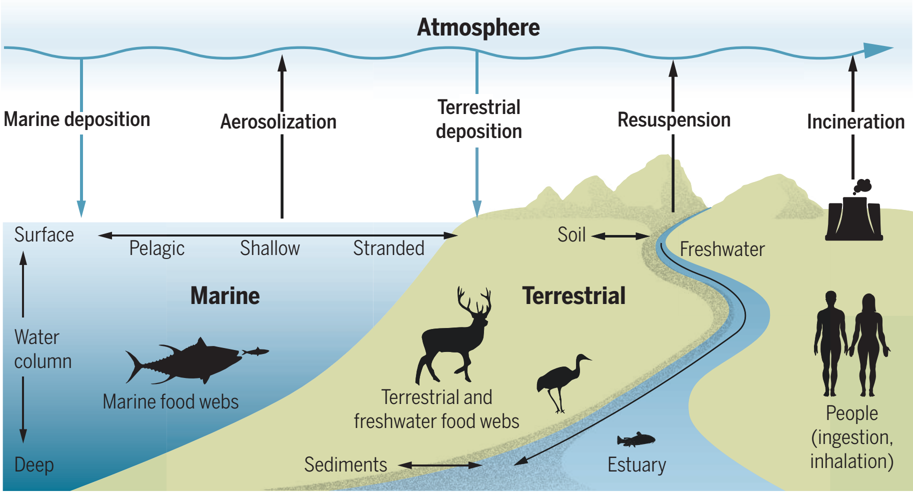
Researchers also must delve deeper into other transport pathways of the microplastic cycle. For example, scientists know little about how microplastics move through terrestrial ecosystems, but evidence suggests percolation from the surface to deeper layers, resuspension into the atmosphere, and transport into ground and surface waters (*9*). In streams, microplastics can be continuously deposited and resuspended, buried in sediments, or exported to downstream ecosystems including lakes, estuaries, and the ocean (*10*). Also, very little is known about how microplastics move through food webs, but some evidence suggests trophic transfer (*11*). Moreover, during their life cycle, microplastics are subject to abiotic and biotic transformations. For example, microbes can incorporate carbon atoms derived from plastic when building their cell membranes (*12*). Microbial breakdown can generate airborne fragments and greenhouse gases, as can degradation (oxidation) by ultraviolet light from the Sun (*13*).

Researchers now recognize that plastic cycles through more than just the ocean. To be sure, the ocean is a sink for microplastics. But as ecologists learn more about these particles, they realize that the ocean is not always the final fate of microplastics; rather, the ocean is one part of the global plastic cycle. In his essay "Odyssey," Aldo Leopold poetically describes how biological, chemical, and geological factors shape the journey of atoms "X" and "Y" (representing carbon and nitrogen) among the land, atmosphere, and sea, between biotic and abiotic compartments, and through deep time. Microplastics might display a different arrangement of atoms, but nonetheless, plastic particles in the environment are subject to the same biogeochemical forces as all other matter.

As ecologists think about all that encompasses the sources, fates, and transformations of microplastics, Leopold's prose challenges them to envision and measure processes among all ecosystem compartments, including those that strain one's imagination, such as plastic in rain. Future microplastic researchers should follow the example of Brahney *et al.* and think big about small particles, so as to contribute to our understanding of the global microplastic cycle and how it has become an aspect of global elemental cycles. ■

Microplastic pollution is pervasive

Emerging research pinpoints atmospheric deposition as a mode of microplastic transfer to the western United States. Mapping microplastic pools (water, land, organisms) and fluxes (arrows) will guide delineation of the global microplastic cycle.



GRAPHIC: N. CARY/SCIENCE

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GENETICS

A gene for color differences between sexes

Sex differences in plumage color in hybrid canaries are controlled by a single enzyme

By **Nancy Chen**

Sexual dimorphism—phenotypic differences between sexes of the same species—is a widespread yet puzzling phenomenon in nature. How such traits evolve has fascinated evolutionary biologists since Darwin, whose ponderings about elaborate ornaments in males prompted him to develop the theory of sexual selection (*1*), and numerous studies have sought to explain the evolution of these traits (*2*). Less is known about the genetic and molecular mechanisms that allow species to generate divergent morphologies from nearly identical genomes (*3*). On page 1270 of this issue, Gazda *et al.* (*4*) show that sex-specific plumage coloration in hybrid canaries is controlled by a single genomic region containing the gene encoding β-carotene oxygenase 2 (*BCO2*). Differences in coloration between the sexes are due to the up-regulation of *BCO2* expression and consequent degradation of pigments in females, demonstrating that color differences between males and females can evolve through a simple molecular mechanism.

One of the most prominent forms of sexual dimorphism is different coloration between males and females, or sexual dichromatism. Indeed, in some species, sex-specific coloration is so divergent that males and females were once considered different species (*1*). Sexual dichromatism is typically thought to arise from sexual selection for increased ornamentation in males (*1*) and, accordingly, is often used as a proxy for the strength of sexual selection in comparative studies (*5*). Alternatively, sexual dichromatism could also arise from natural selection for cryptic coloration in females (*6*). Recent studies indicate that sexual dichromatism is driven by sexual and natural selection operating in both

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