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The Disordered Kinetics of Earth's Carbon Cycle

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The carbon cycle describes the transformations of carbon as it cycles through living organisms and the physical environment. In its simplest form, the cycle amounts to a loop between photosynthesis and respiration. Photosynthesis produces organic carbon and molecular oxygen from carbon dioxide and water. Respiration reverses the process by oxidation of organic carbon. The duration of the cycle spans a vast range of time scales: from days or less for fast-growing plankton in the oceans, to hundreds of millions of years or more for the small fraction of organic matter that is buried as rock. The rates at which the cycle is closed set atmospheric carbon dioxide levels at short time scales and oxygen levels at geologic time scales. Respiration rates thereby influence not only climate—by the determination of equilibrium carbon dioxide concentrations—but also biological evolution—because the oxygenation of Earth's atmosphere must have preceded the advent of aerobic metabolism. We review recent advances in the understanding of the rates that control the carbon cycle, with emphasis on the respiratory back-reaction. Given considerable biological, chemical, and environmental variation, it comes as no surprise that measurements of rates vary greatly. Observations suggest, however, some surprising simplicity: for example, the rates of microbial consumption of organic matter in sediments and soils slow down systematically like the inverse of the age of the organic matter. This aging effect can be quantitatively understood as the macroscopic observation of microscopically disordered kinetics. The disorder can arise purely physically as the consequence of a reaction-diffusion process in porous media, but any combination of physical, chemical, and biological parameters that yield a wide range of rates suffices. A predicted practical consequence is a slow, logarithmic decay of organic matter in sediments and soils, which compares well with measurements. Further observations suggest that the effects of such disordered kinetics extends to inorganic processes as well. The carbon cycle thus appears not as a simple reaction network defined by a single set of rates, but rather as complex network in which the rates of specific reactions can be widely dispersed. We conclude by briefly discussing implications for short-term climate and long-term evolution.