The Soil's Breath

As some scientists probe the skies and oceans for answers to questions about climate change, others are digging deeper into the mysteries of life below the surface

by Tyler Volk

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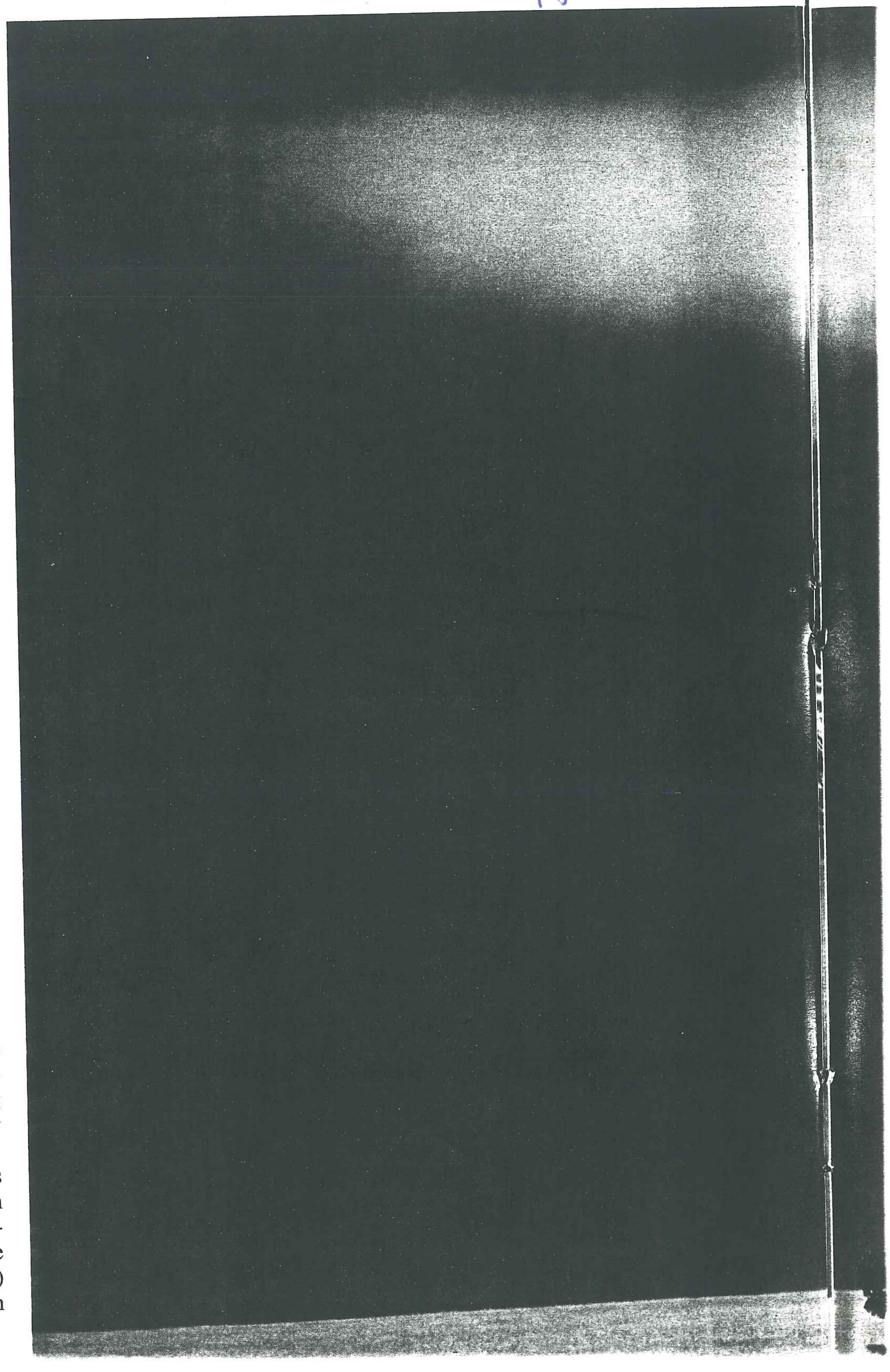


Soil seems like passive stuff when I ramble over it during woodland searches for birds. But when I sit at my computer, assembling data at the planetary scale, the soil reveals itself as one of the most active organs in the earth's "body."

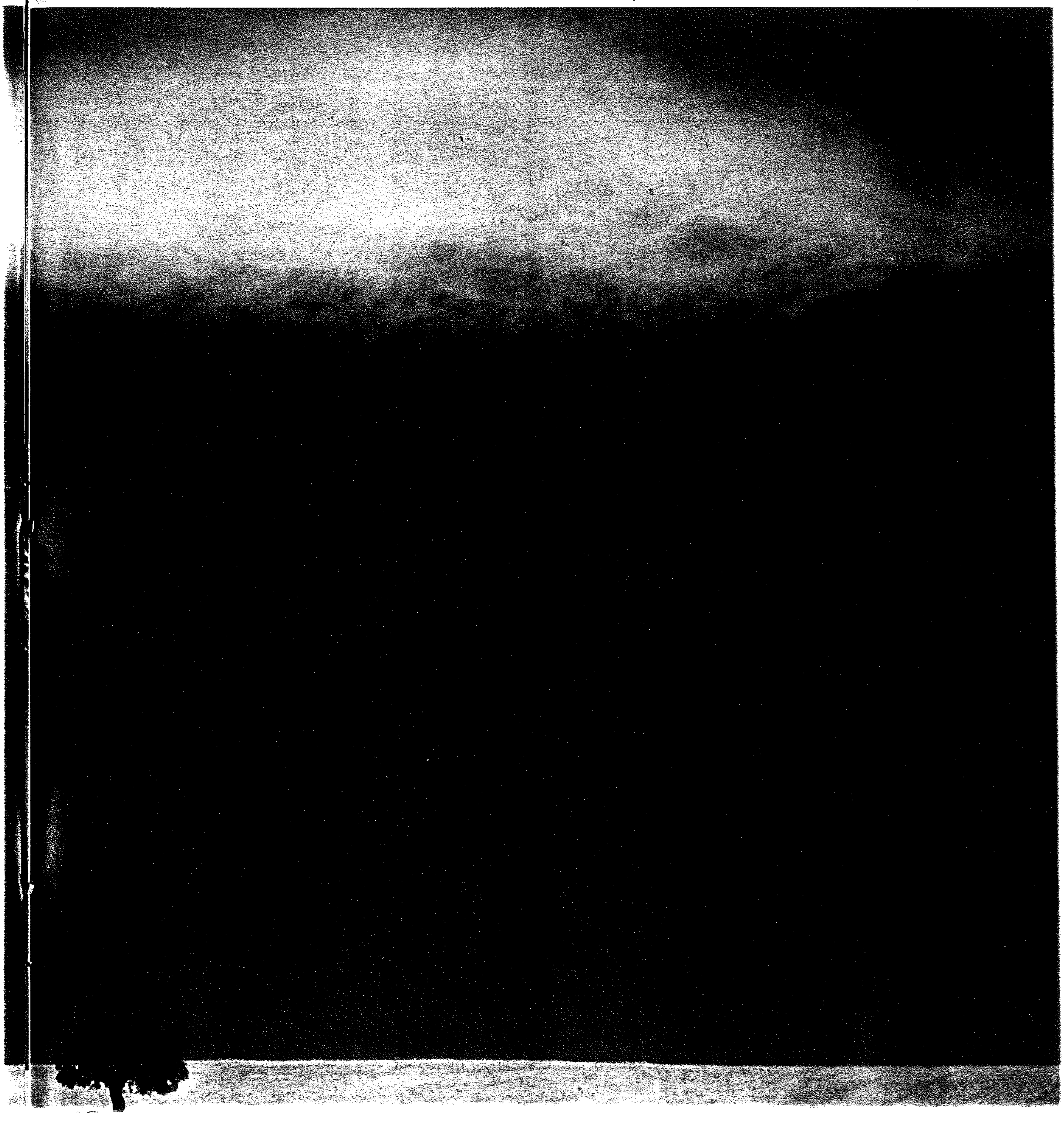
Organisms living on and within the soil—beetles, worms, and other invertebrate creatures, along with fungi, roots, bacteria and other microbes—produce a ceaseless flow of carbon dioxide as they respire. This flood of colorless and odorless gas, the soil's breath, enters the atmosphere and annually exceeds, by more than ten times, the amount of carbon dioxide emitted by all human activities, including the burning of fossil fuels.

For thousands of years, before there were factories, before vast tracts of forest were cleared or burned to grow crops and graze herds of cattle, the various flows of the global carbon cycle were closely balanced. The amount of carbon dioxide that passed from ocean to atmosphere matched that from atmosphere to ocean; the carbon from atmospheric carbon dioxide incorporated into plant tissue during photosynthesis was matched by a return flow during respiration by bacteria, animals, and fungi.

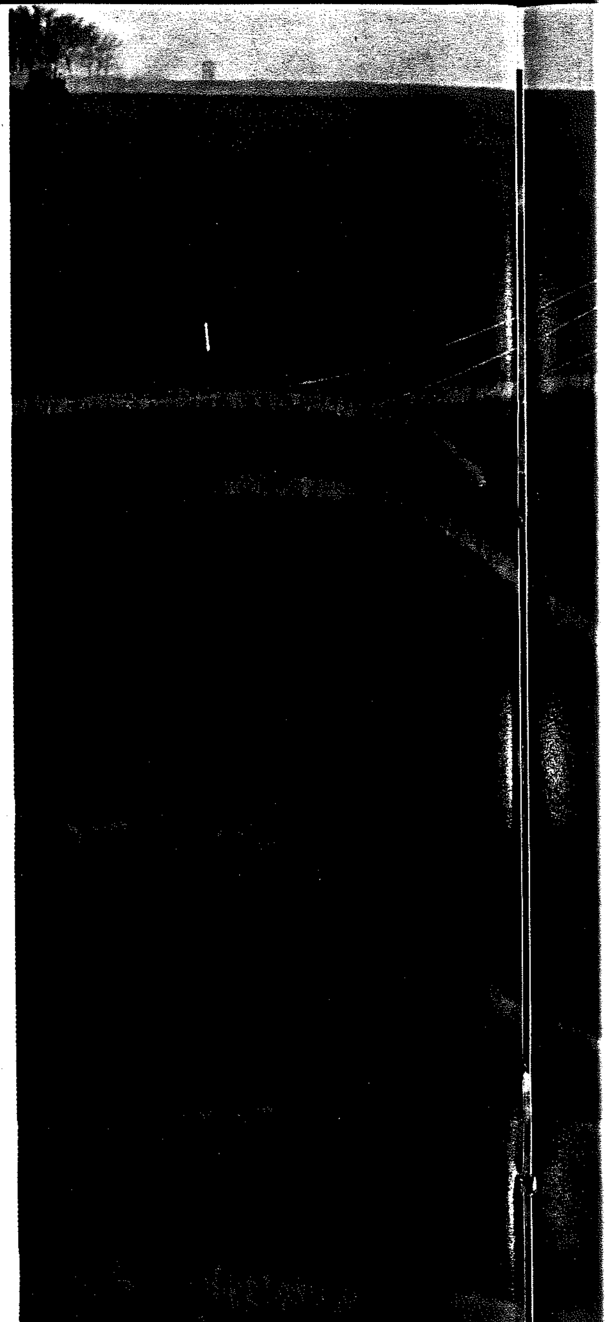
But now—thanks to the industries, homes, and cars that spew out carbon dioxide as a combustion byproduct of their appetites for fossil fuels—the scales have been tipped, and the atmosphere's store of this potent greenhouse gas has been growing. Some (but, crucially, not all) of this new carbon dioxide then continues its journey, spreading through the byways of the global carbon cycle, the constant circulation of the carbon atoms that are essential to life on earth. No one knows for certain just how much new carbon the cycle can absorb without being thrown out of whack or just where the new carbon will wind up.

The great exhalation from earth to air is key to comprehending the role of soil in the global cycle of carbon. Unlike the simple forms of carbon in the atmosphere (the three-atom carbon dioxide, for instance) and in the ocean (primarily the five-atom

Trees take the carbon dioxide they need for photosynthesis from the air around them. Respiring leaves return some of the gas to the atmosphere, while still more passes into the soil as roots respire.
Michael Busselle; Tony Stone Worldwide

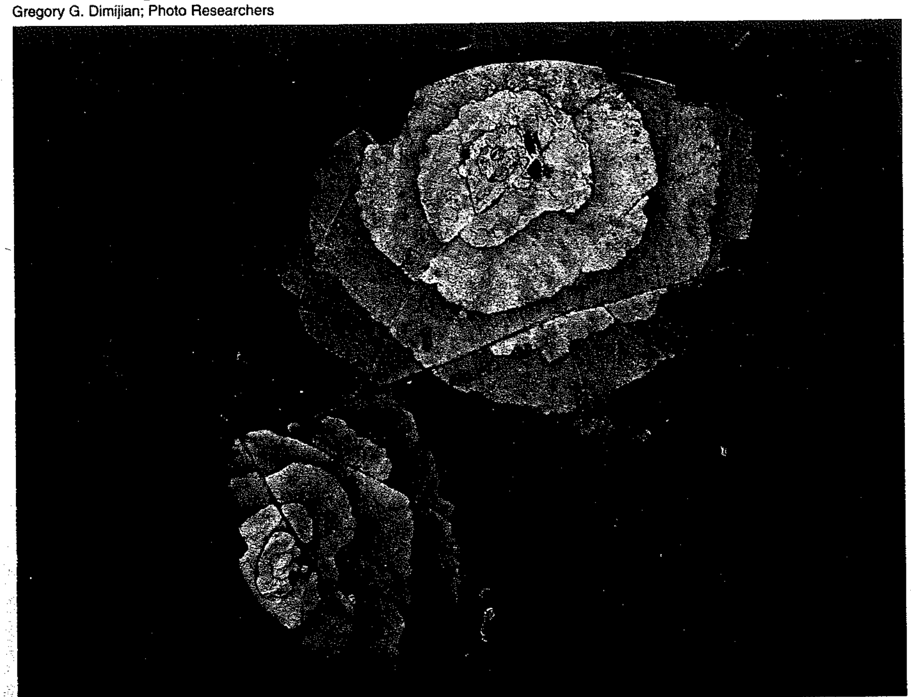


Jim Brandenburg; Minden Pictures

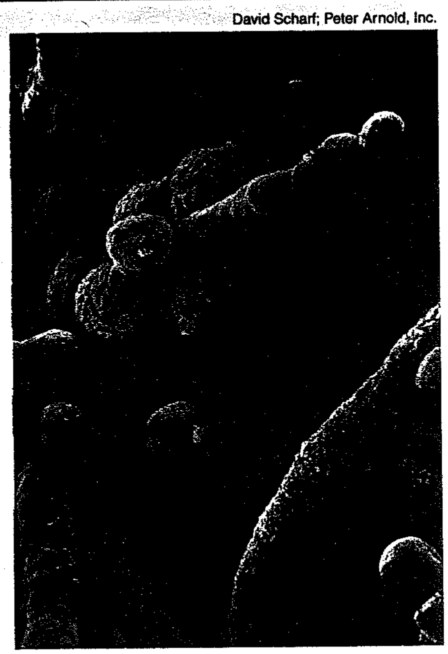


Fungi decompose leaves, below, and other plant debris on the soil's surface, while untold numbers of tiny organisms, including more fungi, bottom, feed on underground stores of organic carbon. When these microorganisms respire, they release carbon dioxide. Right: As tilled fields lie exposed to the sun's warming rays, microbes in the soil go into high gear. A result of the increased microbial respiration is the especially large amounts of CO_2 these fields exhale.

Gregory G. Dimijian; Photo Researchers



David Scharf; Peter Arnold, Inc.



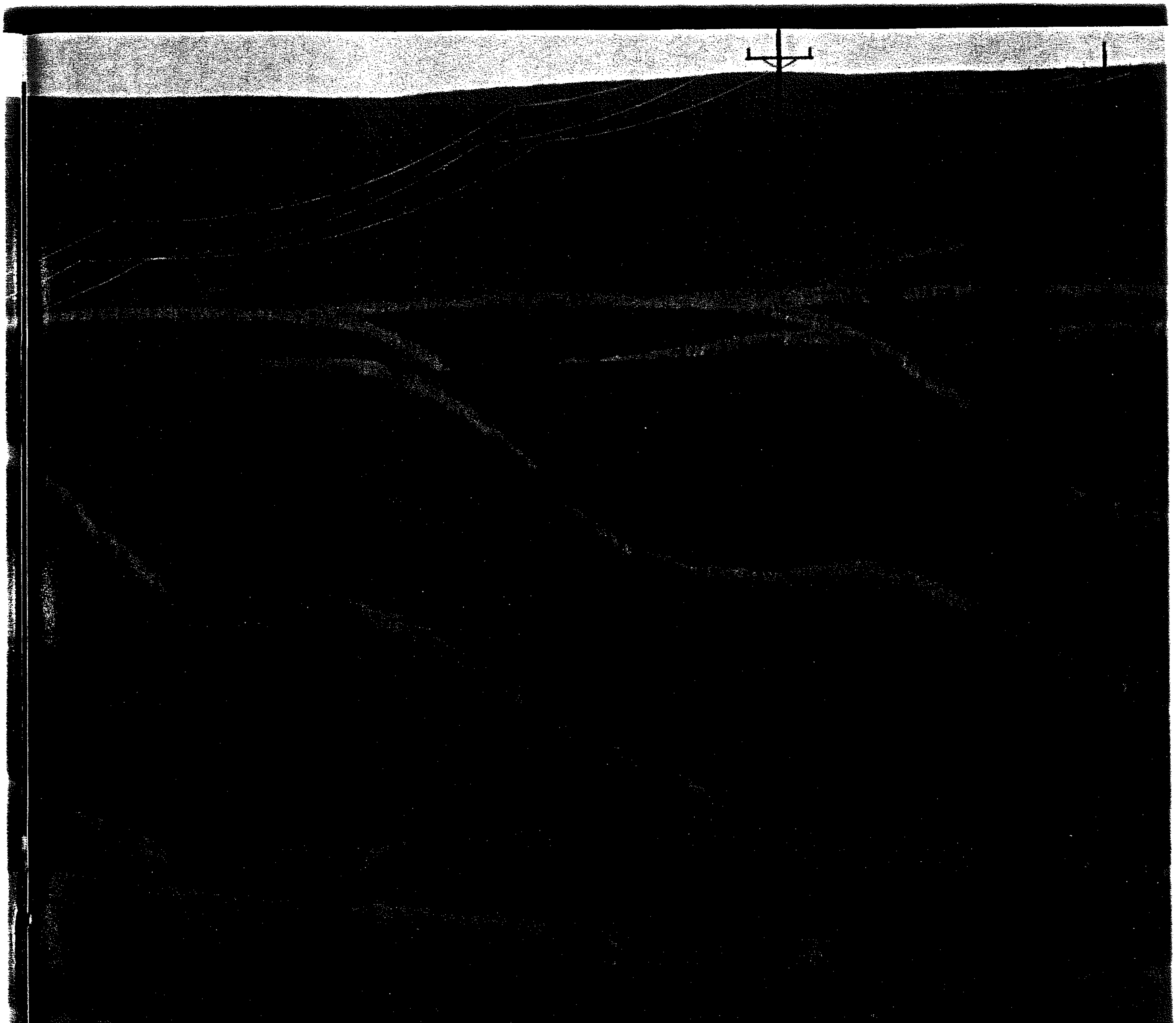
(False-color image; x 4,800)

bicarbonate ion), most carbon in the soil, derived from living matter, is complex, bound into large molecules (long chains of cellulose, massive blobs of protein). Taken together, these partly decomposed, jettisoned tissues of life, called humus, are interwoven into the variegated quilt of soil, along with bits of minerals, tiny organisms, gases, and water. The carbon in humus is what makes soil dark, crumbly, and spongy. Humus, too, gives soil its luscious "earth" aroma.

Soil has so far largely resisted scientific efforts to decipher much of its inner dynamics, but we do know that almost all the earth's store of soil carbon is found within the top three feet (exceptions are the deep carbon stores of tundra and peat bogs). Furthermore, about a third of the gaseous carbon emitted from soil comes from its uppermost layer of decomposing litter. This litter—fallen leaves and twigs, older, overgrown stems of moss, and rotting seed casings—is mined by fungi, worms, bacteria, and other denizens of the surface soil. These organisms and their predators metabolically burn the carbon in the high-energy molecules of litter and release it, linked with oxygen, as carbon dioxide.

The remaining two-thirds of the soil's flux of gaseous carbon is exhaled at deeper levels and must make its way up through the tiny spaces between mineral grains and humus particles. About half comes from the respiration of roots (and from mycorrhizae, the ubiquitous, minuscule fungi intimately associated with roots). Unlike cells in leaves, root cells do not use up carbon dioxide in photosynthesis; instead, like breathing animals, they are overall emitters of the gas. This root respiration is one reason that gases within the soil of a midwestern wheat field in summer contain a concentration of carbon dioxide more than a hundred times that of the atmosphere.

Respiration by soil microbes generates the other major portion of the soil's "deep" breath. These tiny organisms feed on the carbon in organic matter, some of which reaches them when decaying surface litter is worked downward by worms, beetles, and other soil dwellers. But the largest source of this high-energy organic carbon is already deep within the soil in the form of roots and their associated fungi. Small



roots and fine root hairs in particular are continually withering away as local pockets of soil become depleted of moisture or nutrients. As roots decompose, carbon directly enters into the soil at many depths. We expect to find deep roots in forests, but even grasslands support a pool of soil carbon that may exceed in depth the upward reach of the stems and seed heads.

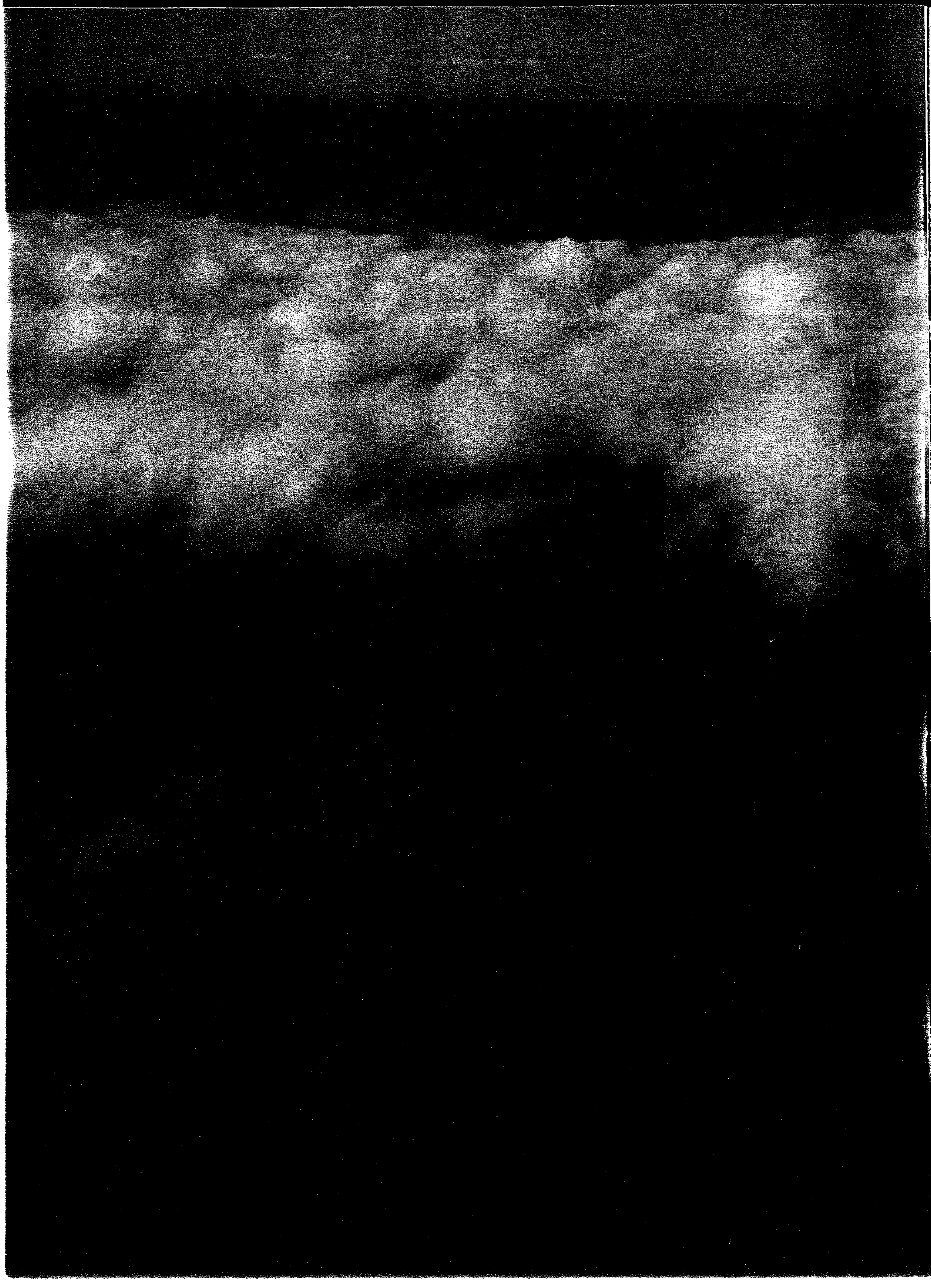
Whatever the source of the soil carbon, microbes spend their short lifetimes transforming it into carbon dioxide. Most of these humus-digesting microbes have not been named or, indeed, even isolated by scientists because they cannot be kept alive outside the complex matrix of associations in their soil habitats.

Taken together, the exhalations of microbes, roots, fungi, earthworms, and other organisms generate one side of the "budget" for the soil's carbon pool. What about the other side? In general, for a pool to maintain itself, outbound flows must be balanced by those inbound. Root respiration, for example, depends upon the products of photosynthesis sent downward through stems and trunks. Similarly, the microbes and other organisms at the surface and deeper in the soil are supplied by photosynthesis with the litter that falls and the roots that die. Altogether, the 60 billion tons of carbon in the carbon dioxide vented from the soil each year are nearly equal to the annual amount of carbon bound into the tissues of land plants globally. (Estimates place the products of photosynthesis consumed by aboveground herbivores at less than 10 percent of the total.)

How do the incoming flux from photosynthesis and the outgoing soil's breath affect the amount of carbon stored in the soil? Earthwide, the amount of carbon in humus is two to three times the amount of carbon in atmospheric carbon dioxide. However, the pool's mass varies from place to place by more than tenfold. Why?

Generally, the more you eat, the wider your girth. And all else being equal, a soil fed more organic matter by its plants will contain more soil carbon. But all else is rarely equal. Some people remain rails no matter how many milk shakes they slurp, while others remain obese even on highly reduced diets. The difference is in the rate of metabolism, a difference that can determine the bulk of carbon in soils, too.

The rate at which soils consume the carbon received from plant tissue is linked to environmental conditions, such as temper-



For all their lush vegetation, tropical rain forests store little carbon in the soil. Warm temperatures and abundant moisture mean that organisms in the surface litter and in the soil remain active year-round, providing few opportunities for carbon to build up.
Will and Deni McIntyre; Photo Researchers, Inc.

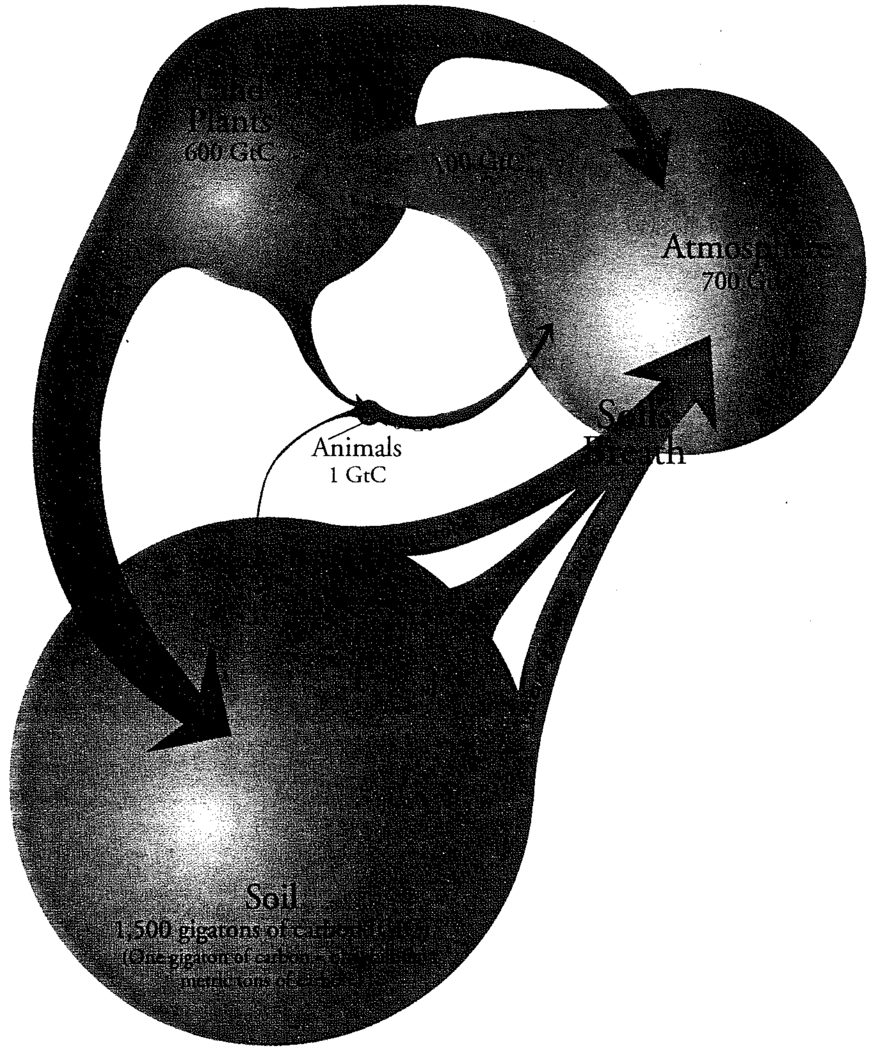
ature, rainfall, and soil structure, that influence the activity of the soil microbes, the organisms that contribute most to the soil's breath. Chief among these conditions is temperature. When warm, the microbes become even more active and frenetically transform soil carbon into carbon dioxide, which then flushes into the air.

A vivid example of the effect of temperature on this flushing is the difference in the soil carbon of tropical grasslands, or savannas, and that of temperate grasslands. On average, helped by a more intense sun, the savannas grow about 50 percent more material than do grasslands in the higher latitudes (45 grams of carbon per square foot per year compared with 30 grams). But savannas have roughly only a fifth the soil carbon of temperate grasslands (400 grams per square foot versus 2,000 grams). The reason for this striking difference is that at high latitudes, microbial activity slows to a near standstill during the cold winter, reducing the exhalation of soil carbon. The resultant bigger pool of carbon remaining in the ground contributes to the richness and fertility we admire in prairie soils.

Human activities, especially since the invention of the plow, also affect the balance between the inflow of fresh organic materials to the soil and the outflow of carbon dioxide, and thus the mass of organic soil matter. As a farmer tills the fields, the soil tends to become warmer and more aerated, which increases the rate of decomposition. On average, soils brought under cultivation lose about a fourth of their carbon pool before settling into a new steady state. Careful management, on the other hand, can increase carbon retention. Gardeners, for instance, often more than compensate for tilling by adding compost and manure.

Large-scale shifts in the soil's breath are under scrutiny as indicators—and perhaps amplifiers—of global change. The anticipated trend of rising temperatures as a result of the increasing carbon dioxide will certainly invigorate the exhalation from earth to air. Already we have indications of a dramatic change in the tundra soil of

Carbon Flux and the Soil



About 60 billion metric tons of carbon enter the soil every year, mostly in the form of fallen plant matter and photosynthesized "food" sent from the leaves of plants down into the roots. (The relatively small flux of carbon from animals to the soil is not quantified in the diagram.) An approximately equal amount exits annually in the form of carbon dioxide as soil organisms respire. However, human activities, such as the burning of fossil fuels, are adding dramatically to the amount of CO_2 in the atmosphere. How soil and other components of the carbon cycle will be affected by the increase is still unknown.
Source: Tyler Volk. Estimates represent an idealized, balanced condition. Diagram excludes oceans.

Leaves cover the ground in a French forest. Rising levels of atmospheric CO_2 may affect how long the carbon in this decaying foliage will be stored in the soil.
Michael Busselle; Tony Stone Worldwide

Alaska. Based on corings and gas measurements, this polar soil, which had been storing carbon since the glaciers melted ten thousand years ago, has switched to being a net source to the atmosphere. Based on knowledge of microbial activity as a function of temperature, some researchers estimate that the observed warming of about one degree Fahrenheit during the twentieth century could already have increased the amount of carbon dioxide coming from the soil by about a billion tons per year, or about a sixth of our own production of the gas from fossil fuels.

In addition to changes in the outgoing flux from the soil's carbon pool, might there be changes in the incoming flux—for example, from the direct effect of carbon dioxide on photosynthesis? For most plants, more carbon dioxide in the air stimulates photosynthesis by boosting the pressure that drives the gas into the leaves, where it is used to produce organic matter such as starch, cellulose, and protein. Every species will respond differently, some adjusting better than others to changing circumstances. Depending on their responses to increased CO_2, some species may drop out completely and others may expand their range to become new members of plant communities.

Scientists studying the carbon cycle have been calculating just how much carbon to subtract from their budget sheets for the atmosphere, specifically from the carbon dioxide fertilization. The best estimates thus far tally about one billion tons of additional carbon entering storage in such forms as tree trunks, ground litter, and soil humus. Thus, as a bottom line, the increased soil's breath attributable today to rising global temperatures might just be balanced by an increased flux to storage—if we are lucky. Of course, for a complete prediction of atmospheric carbon dioxide, we still have to examine deforestation, reforestation, entry and exit zones of carbon dioxide to and from the ocean, the dissolution of minerals, energy technologies, and the politics of international responsibility. But these are still other stories in the ongoing saga of the carbon cycle. □