TWO

Skin of the Earth

We know more about the movement of
celestial bodies than about the soil underfoot.

LEONARDO DA VINCI

CHARLES DARWIN'S LAST AND LEAST-KNOWN BOOK was not particularly controversial. Published a year before he died in 1882, it focused on how earthworms transform dirt and rotting leaves into soil. In this final work Darwin documented a lifetime of what might appear to be trivial observations. Or had he discovered something fundamental about our world—something he felt compelled to spend his last days conveying to posterity? Dismissed by some critics as a curious work of a decaying mind, Darwin's worm book explores how the ground beneath our feet cycles through the bodies of worms and how worms shaped the English countryside.

His own fields provided Darwin's first insights into how worms attain geologic significance. Soon after returning home to England from his voyage around the world, the famous gentleman farmer noticed the resemblance between the stuff worms periodically brought up to the surface and the fine earth that buried a layer of cinders strewn about his meadows years before. Yet since then nothing had happened in these fields, for in them Darwin kept no livestock and grew no crops. How were the cinders that once littered the ground sinking right before his eyes?

About the only explanation that seemed plausible was simply preposterous. Year after year, worms brought small piles of castings up to the surface. Could worms really be plowing his fields? Intrigued, he began investigating whether worms could gradually build up a layer of new soil. Some of his contemporaries thought him crazy—a fool obsessed with the idea that the work of worms could ever amount to anything.

Undeterred, Darwin collected and weighed castings to estimate how much dirt worms moved around the English countryside. His sons helped him examine how fast ancient ruins sank into the ground after they were abandoned. And, most curiously to his friends, he observed the habits of worms kept in jars in his living room, experimenting with their diet and measuring how rapidly they turned leaves and dirt into soil. Darwin eventually concluded that "all the vegetable mould over the whole country has passed many times through, and will again pass many times through, the intestinal canal of worms."[1] It's a pretty big leap to spring from a suspicion about how worms tilled his fields to thinking that they regularly ingested all of England's soil. What led him down this path of unconventional reasoning?

One example in particular stands out among Darwin's observations. When one of his fields was plowed for the last time in 1841, a layer of stones that covered its surface clattered loudly as Darwin's young sons ran down the slope. Yet in 1871, after the field lay fallow for thirty years, a horse could gallop its length and not strike a single stone. What had happened to all those clattering rocks?

Intrigued, Darwin cut a trench across the field. A layer of stones just like those that had once covered the ground lay buried beneath two and a half inches of fine earth. This was just what had happened to the cinders decades before. Over the years, new topsoil built up—a few inches per century—thanks, Darwin suspected, to the efforts of countless worms.

Curious as to whether his fields were unusual, Darwin enlisted his now grown sons to examine how fast the floors and foundations of buildings abandoned centuries before had been buried beneath new soil. Darwin's scouts reported that workmen in Surrey discovered small red tiles typical of Roman villas two and a half feet beneath the ground surface. Coins dating from the second to fourth centuries confirmed that the villa had been abandoned for more than a thousand years. Soil covering the floor of this ruin was six to eleven inches thick, implying it formed at a rate of half an inch to an inch per century. Darwin's fields were not unique.

Observations from other ancient ruins reinforced Darwin's growing belief that worms plowed the English countryside. In 1872 Darwin's son William found that the pavement in the nave of Beaulieu Abbey, which had been destroyed during Henry VIII's war against the Catholic Church, lay six to twelve inches below ground. The ruins of another large Roman

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villa in Gloucestershire lay undetected for centuries, buried two to three feet under the forest floor until rediscovered by a gamekeeper digging for rabbits. The concrete pavement of the city of Uriconium also lay under almost two feet of soil. These buried ruins confirmed that it took centuries to form a foot of topsoil. But were worms really up to the task?

As Darwin collected and weighed worm castings in a variety of places, he found that each year they brought up ten to twenty tons of earth per acre. Spread across the land in an even layer, all that dirt would pile up a tenth of an inch to a quarter of an inch each year. This was more than enough to explain the burial of Roman ruins and was close to the soil formation rates he'd deduced in what his kids called the stony field. Based on watching and digging in his own fields, excavating the floors of ancient buildings, and directly weighing worm castings, Darwin found that worms played an instrumental role in forming topsoil.

But how did they do it? In the terrariums packed into his cramped living room, Darwin watched worms introduce organic matter into the soil. He counted the huge number of leaves his new pets drew into their burrows as edible insulation. Tearing leaves into small pieces and partially digesting them, worms mixed organic matter with fine earth they had already ingested.

Darwin noticed that in addition to grinding up leaves, worms break small rocks down into mineral soil. When dissecting worm gizzards, he almost always found small rocks and grains of sand. Darwin discovered that the acids in worm stomachs matched humic acids found in soils, and he compared the digestive ability of worms to the ability of plant roots to dissolve even the hardest rocks over time. Worms, it seemed, helped make soil by slowly plowing, breaking up, reworking, and mixing dirt derived from fresh rocks with recycled organic matter.

Darwin discovered that worms not only helped make soil, they helped move it. Prowling his estate after soaking rains he saw how wet castings spread down even the gentlest slopes. He carefully collected, weighed, and compared the mass of castings ejected from worm burrows and found that twice as much material ended up on the downslope side. Material brought up by worms moved an average of two inches downhill. Simply by digging their burrows worms pushed stuff downhill little by little.

Based on his measurements, Darwin calculated that each year a pound of soil would move downslope through each ten-yard-long stretch of a typical English hillslope. He concluded that all across England, a blanket of dirt slowly crept down turf-covered hillsides as an unseen army of worms reworked the soil. Together, English and Scottish worms moved almost half a billion tons of earth each year. Darwin considered worms a major geologic force capable of reshaping the land over millions of years.

Even though his work with worms was, obviously, groundbreaking, Darwin didn't know everything about erosion. He used measurements of the sediment moved by the Mississippi River to calculate that it would take four and a half million years to reduce the Appalachian Mountains to a gentle plain—as long as no uplift occurred. We now know that the Appalachians have been around for over a hundred million years. Geologically dead and no longer rising, they have been eroding away since the time of the dinosaurs. So Darwin massively underestimated the time required to wear down mountains. How could he have been off by so much?

Darwin and his contemporaries didn't know about isostasy—the process through which erosion triggers the uplift of rocks from deep within the earth. The idea didn't enter mainstream geologic thought until decades after his death. Now well accepted, isostasy means that erosion not only removes material, it also draws rock up toward the ground surface to replace most of the lost elevation.

Though at odds with a commonsense understanding of erosion as wearing the world down, isostasy makes sense on a deeper level. Continents are made of relatively light rock that "floats" on Earth's denser mantle. Just like an iceberg at sea, or an ice cube in a glass of water, most of a continent rides down below sea level. Melt off the top of floating ice and what's left rises up and keeps floating. Similarly, the roots of continents can extend down more than fifty miles into the earth before reaching the denser rocks of the mantle. As soil erodes off a landscape, fresh rock rises up to compensate for the mass lost to erosion. The land surface actually drops by only two inches for each foot of rock removed because ten inches of new rock rise to replace every foot of rock stripped off the land. Isostasy provides fresh rock from which to make more soil.

Darwin considered topsoil to be a persistent feature maintained by a balance between soil erosion and disintegration of the underlying rock. He saw topsoil as continuously changing, yet always the same. From watching worms, he learned to see the dynamic nature of Earth's thin blanket of dirt. In this final chapter of his life, Darwin helped open the door for the modern view of soil as the skin of the Earth.

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> When we behold a wide, turf-covered expanse, we should remember that its smoothness, on which so much of its beauty depends, is mainly due to all the inequalities having been slowly leveled by worms. It is a marvelous reflection that the whole of the superficial mould over any such expanse has passed, and will again pass, every few years through the bodies of worms. The plough is one of the most ancient and valuable of man's inventions; but long before he existed the land was in fact regularly ploughed, and still continues to be thus ploughed by earthworms. It may be doubted whether there are many other animals which have played so important a part in the history of the world, as have these lowly organised creatures.[2]

Recent studies of the microscopic texture of soils in southeastern Scotland and the Shetland Islands confirm Darwin's suspicions. The topsoil in fields abandoned for several centuries consists almost entirely of worm excrement mixed with rock fragments. As Darwin suspected, it takes worms just a few centuries to thoroughly plow the soil.

Darwin's conception of soil as a dynamic interface between rock and life extended to thinking about how soil thickness reflects local environmental conditions. He described how a thicker soil protects the underlying rocks from worms that penetrate only a few feet deep. Similarly, Darwin noted that the humic acids worms inject into the soil decay before they percolate very far down into the ground. He reasoned that a thick soil would insulate rocks from extreme variations in temperature and the shattering effects of frost and freezing. Soil thickens until it reaches a balance between soil erosion and the rate at which soil-forming processes transform fresh rock into new dirt.

This time Darwin got it right. Soil is a dynamic system that responds to changes in the environment. If more soil is produced than erodes, the soil thickens. As Darwin envisioned, accumulating soil eventually reduces the rate at which new soil forms by burying fresh rock beyond the reach of soil-forming processes. Conversely, stripping the soil off a landscape allows weathering to act directly on bare rock, either leading to faster soil formation or virtually shutting it off, depending on how well plants can colonize the local rock.

Given enough time, soil evolves toward a balance between erosion and the rate at which weathering forms new soil. This promotes development of a characteristic soil thickness for the particular environmental circumstances of a given landscape. Even though a lot of soil may be eroded and

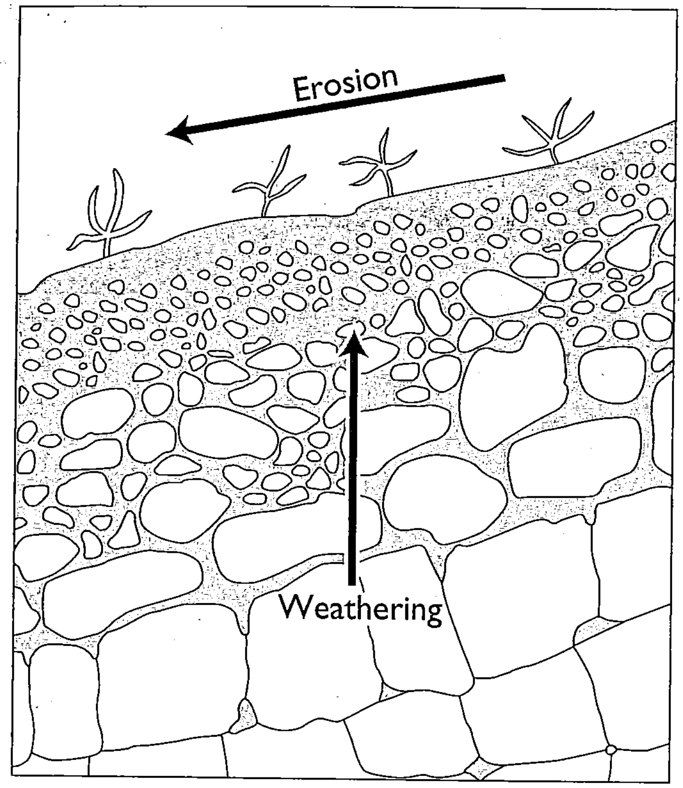
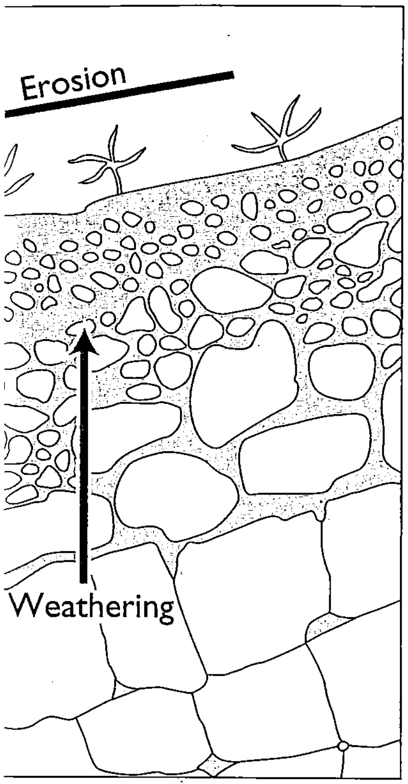


Figure 1. The thickness of hillslope soils represents the balance between their erosion and the weathering of rocks that produces soil.

replaced through weathering of fresh rock, the soil, the landscape, and whole plant communities evolve together because of their mutual interdependence on the balance between soil erosion and soil production.

Such interactions are apparent even in the form of the land itself. Bare angular hillslopes characterize arid regions where the ability of summer thunderstorms to remove soil chronically exceeds soil production. In wetter regions where rates of soil production can keep up with soil erosion, the form of rounded hills reflects soil properties instead of the character of underlying rocks. So arid landscapes where soil forms slowly tend to have angular hillslopes, whereas humid and tropical lands typically have gentle, rolling hills.



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Soil not only helps shape the land, it provides a source of essential nutrients in which plants grow and through which oxygen and water are supplied and retained. Acting like a catalyst, good dirt allows plants to capture sunlight and convert solar energy and carbon dioxide into the carbohydrates that power terrestrial life right on up the food chain.

Plants need nitrogen, potassium, phosphorus, and a host of other elements. Some, like calcium or sodium, are common enough that their scarcity does not limit plant growth. Others, like cobalt, are quite rare and yet essential. The processes that create soil also cycle nutrients through ecosystems, and thereby indirectly make the land hospitable to animals as well as plants. Ultimately, the availability of soil nutrients constrains the productivity of terrestrial ecosystems. The whole biological enterprise of life outside the oceans depends on the nutrients soil produces and retains. These circulate through the ecosystem, moving from soil to plants and animals, and then back again into the soil.

The history of life is inextricably related to the history of soil. Early in Earth's history bare rock covered the land. Rainwater infiltrating down into barren ground slowly leached elements out of near-surface materials, transforming rock-forming minerals into clays. Water slowly percolating down through soils redistributed the new clays, forming primitive mineral soils. The world's oldest fossil soil is more than three billion years old, almost as old as the most ancient sedimentary rock and probably land itself. Clay formation appears to have dominated early soil formation; the earliest fossil soils are unusually rich in potassium because there were no plants to remove nutrients from the clays.

Some scientists have proposed that clay minerals even played a key role in the evolution of life by providing highly reactive surfaces that acted as a substrate upon which organic molecules assembled into living organisms. The fossil record of life in marine sediments extends back to about the same time as the oldest soil. Perhaps it is no coincidence that guanine and cytosine (two of the four key bases in DNA) form in clay-rich solutions. Whether or not the breakdown of rocks into clays helped kick-start life, evolution of the earliest soils played a key role in making Earth inhabitable for more complex life.

Four billion years ago Earth's surface temperature was close to boiling. The earliest bacteria were close relatives of those that still carpet Yellowstone's spectacular thermal pools. Fortunately, the growth and development of these heat-loving bacteria increased weathering rates enough to form primitive soils on rocks protected beneath bacterial mats. Their consumption of atmospheric carbon dioxide cooled the planet by 30°C to 45°C—an inverse greenhouse effect. Earth would be virtually uninhabitable were it not for these soil-making bacteria.

The evolution of soils allowed plants to colonize the land. Some 350 million years ago, primitive plants spread up deltas and into coastal valleys where rivers deposited fresh silt eroded off bare highlands. Once plants reached hillsides and roots bound rock fragments and dirt together, primitive soils promoted the breakdown of rocks to form more soil. Respiration by plant roots and soil biota raised carbon dioxide levels ten to a hundred times above atmospheric levels, turning soil water into weak carbonic acid. Consequently, rocks buried beneath vegetation-covered soils decayed much faster than bare rock exposed at the surface. The evolution of plants increased rates of soil formation, which helped create soils better suited to support more plants.

Once organic matter began to enrich soils and support the growth of more plants, a self-reinforcing process resulted in richer soil better suited to grow even more plants. Ever since, organic-rich topsoil has sustained itself by supporting plant communities that supply organic matter back to the soil. Larger and more abundant plants enriched soils with decaying organic matter and supported more animals that also returned nutrients to the soil when they too died. Despite the occasional mass extinction, life and soils symbiotically grew and diversified through climate changes and shifting arrangements of continents.

As soil completes the cycle of life by decomposing and recycling organic matter and regenerating the capacity to support plants, it serves as a filter that cleanses and converts dead stuff into nutrients that feed new life. Soil is the interface between the rock that makes up our planet and the plants and animals that live off sunlight and nutrients leached out of rocks. Plants take carbon directly from the air and water from the soil, but just as in a factory, shortages of essential components limit soil productivity. Three elements—nitrogen, potassium, and phosphorus—usually limit plant growth and control the productivity of whole ecosystems. But in the big picture, soil regulates the transfer of elements from inside the earth to the surrounding atmosphere. Life needs erosion to keep refreshing the soil—just not so fast as to sweep it away altogether.

At the most fundamental level, terrestrial life needs soil—and life plus dirt, in turn, make soil. Darwin estimated that almost four hundred pounds of worms lived in an acre of good English soil. Rich topsoil also harbors microorganisms that help plants get nutrients from organic mat-

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ter and mineral soil. Billions of microscopic bugs can live in a handful of topsoil; those in a pound of fertile dirt outnumber Earth's human population. That's hard to imagine when you're packed into the Tokyo subway or trying to make your way down the streets of Calcutta or New York City. Yet our reality is built on, and in many ways depends upon, the invisible world of microbes that accelerate the release of nutrients and decay of organic matter, making the land hospitable for plants and therefore people.

Tucked away out of sight, soil-dwelling organisms account for much of the biodiversity of terrestrial ecosystems. Plants supply underground biota with energy by providing organic matter through leaf litter and the decay of dead plants and animals. Soil organisms, in turn, supply plants with nutrients by accelerating rock weathering and the decomposition of organic matter. Unique symbiotic communities of soil-dwelling organisms form under certain plant communities. This means that changes in plant communities lead to changes in the soil biota that can affect soil fertility and, in turn, plant growth.

Along with Darwin's worms, an impressive array of physical and chemical processes help build soil. Burrowing animals—like gophers, termites, and ants—mix broken rock into the soil. Roots pry rocks apart. Falling trees churn up rock fragments and mix them into the soil. Formed under great pressure deep within the earth, rocks expand and crack apart as they near the ground. Big rocks break down into little rocks and eventually into their constituent mineral grains owing to stresses from wetting and drying, freezing and thawing, or heating by wildfires. Some rock-forming minerals, like quartz, are quite resistant to chemical attack. They just break down into smaller and smaller pieces of the same stuff. Other minerals, particularly feldspars and micas, readily weather into clays.

Too small to see individually, clay particles are small enough for dozens to fit on the period at the end of this sentence. All those microscopic clays fit together tightly enough to seal the ground surface and promote runoff of rainwater. Although fresh clay minerals are rich in plant nutrients, once clay absorbs water it holds onto it tenaciously. Clay-rich soils drain slowly and form a thick crust when dry. Far larger, even the smallest sand grains are visible to the naked eye. Sandy soil drains rapidly, making it difficult for plants to grow. Intermediate in size between sand and clay, silt is ideal for growing crops because it retains enough water to nourish plants, yet drains quickly enough to prevent waterlogging. In particular, the mix of clay, silt, and sand referred to as loam makes the ideal agricultural soil because it allows for free air circulation, good drainage, and easy access to plant nutrients.

Clay minerals are peculiar in that they have a phenomenal amount of surface area. There can be as much as two hundred acres of mineral surfaces in half a pound of clay. Like the thin pieces of paper that compose a deck of cards, clay is made up of layered minerals with cations—like potassium, calcium, and magnesium—sandwiched in between silicate sheets. Water that works its way into the clay structure can dissolve cations, contributing to a soil solution rich in plant-essential nutrients.

Fresh clays therefore make for fertile soil, with lots of cations loosely held on mineral surfaces. But as weathering continues, more of the nutrients get leached from a soil as fewer elements remain sandwiched between the silicates. Eventually, few nutrients are left for plants to use. Although clays can also bind soil organic matter, replenishing the stock of essential nutrients like phosphorus and sulfur depends on weathering to liberate new nutrients from fresh rock.

In contrast, most nitrogen enters soils from biological fixation of atmospheric nitrogen. While there is no such thing as a nitrogen-fixing plant, bacteria symbiotic with plant hosts, like clover (to name but one), reduce inert atmospheric nitrogen to biologically active ammonia in root nodules 2–3 mm long. Once incorporated into soil organic matter, nitrogen can circulate from decaying things back into plants as soil microflora secrete enzymes that break down large organic polymers into soluble forms, such as amino acids, that plants can take up and reuse.

How fast soil is produced depends on environmental conditions. In 1941 UC Berkeley professor Hans Jenny proposed that the character of a soil reflected topography, climate, and biology superimposed on the local geology that provides raw materials from which soil comes. Jenny identified five key factors governing soil formation: parent material (rocks), climate, organisms, topography, and time.

The geology of a region controls the kind of soil produced when rocks break down, as they eventually must when exposed at the earth's surface. Granite decomposes into sandy soils. Basalt makes clay-rich soils. Limestone just dissolves away, leaving behind rocky landscapes with thin soils and lots of caves. Some rocks weather rapidly to form thick soils; others resist erosion and only slowly build up thin soils. Because the nutrients available to plants depend on the chemical composition of the soil's parent material, understanding soil formation begins with the rocks from which the soil originates.

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Topography also affects the soil. Thin soils with fresh minerals blanket slopes in areas where geologic activity raised mountains and continues to steepen slopes. The gentle slopes of geologically quieter landscapes tend to have thicker, more deeply weathered soils.

Climate strongly influences soil formation. High rainfall rates and hot temperatures favor chemical weathering and the conversion of rock-forming minerals into clays. Cold climates accelerate the mechanical breakdown of rocks into small pieces through expansion and contraction during freeze-thaw cycles. At the same time, cold temperatures retard chemical weathering. So alpine and polar soils tend to have lots of fresh mineral surfaces that can yield new nutrients, whereas tropical soils tend to make poor agricultural soils because they consist of highly weathered clays leached of nutrients.

Temperature and rainfall primarily control the plant communities that characterize different ecosystems. At high latitudes, perpetually frozen ground can support only the low scrub of arctic tundra. Moderate temperatures and rainfall in temperate latitudes support forests that produce organic-rich soils by dropping their leaves to rot on the ground. Drier grassland soils that support a lot of microbial activity receive organic matter both from the recycling of dead roots and leaves and from the manure of grazing animals. Arid environments typically have thin rocky soils with sparse vegetation. Hot temperatures and high rainfall near the equator produce lush rainforests growing on leached-out soils by recycling nutrients derived from weathering and recycled from decaying vegetation. In this way global climate zones set the template upon which soils and vegetation communities evolved.

Differences in geology and climate make soils in different regions more or less capable of sustained agriculture. In particular, the abundant rainfall and high weathering rates on the gentle slopes of many tropical landscapes mean that after enough time, rainfall seeping into the ground leaches out almost all of the nutrients from both the soil and the weathered rocks beneath the soil. Once this happens, the lush vegetation essentially feeds on itself, retaining and recycling nutrients inherited from rocks weathered long ago. As most of the nutrients in these areas reside not in the soil but in the plants themselves, once the native vegetation disappears, so does the productive capacity of the soil. Often too few nutrients remain to support crops or livestock within decades of deforestation. Nutrient-poor tropical soils illustrate the general rule that life depends on recycling past

Humans have not yet described all the species present in any natural soil. Yet soils and the biota that inhabit them provide clean drinking water, recycle dead materials into new life, facilitate the delivery of nutrients to plants, store carbon, and even remediate wastes and pollutants—as well as produce almost all of our food.

Out of sight and out of mind, soil-dwelling organisms can be greatly influenced by agricultural practices. Tilling the soil can kill large soil-dwelling organisms, and reduce the number of earthworms. Pesticides can exterminate microbes and microfauna. Conventional short-rotation, single-crop farming can reduce the diversity, abundance, and activity of beneficial soil fauna, and indirectly encourage proliferation of soilborne viruses, pathogens, and crop-eating insects. Generally, so-called alternative agricultural systems tend to better retain soil-dwelling organisms that enhance soil fertility.

Like soil formation, soil erosion rates depend on soil properties inherited from the parent material (rocks), and the local climate, organisms, and topography. A combination of textural properties determines a soil's ability to resist erosion: its particular mix of silt, sand, or clay, and binding properties from aggregation with soil organic matter. Higher organic matter content inhibits erosion because soil organic matter binds soil particles together, generating aggregates that resist erosion. A region's climate influences erosion rates through how much precipitation falls and whether it flows off the land as rivers or glaciers. Topography matters as well; all other things being equal, steeper slopes erode faster than gentle slopes. However, greater rainfall not only generates more runoff, and therefore more erosion, it also promotes plant cover that protects the soil from erosion. This basic trade-off means that the amount of rainfall does not simply dictate the pace of soil erosion. Wind can be a dominant erosion process in arid environments or on bare disturbed soil, like agricultural fields. Biological processes, whether Darwin's worms or human activities such as plowing, also gradually move soil downslope.

Although different types of erosional processes are more or less important in different places, a few tend to dominate. When rain falls onto the ground it either sinks into the soil or runs off over it; greater runoff leads to more erosion. Where enough runoff accumulates, flowing sheets of water can pick up and transport soil, carving small channels, called rills, which collect into larger, more erosive gullies—the name for incised channels large enough that they cannot be plowed over. On steep slopes, intense or sustained rainfall can saturate soil enough to trigger landsliding.

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osion rates depend on soil properties inher- (rocks), and the local climate, organisms, and of textural properties determines a soil's abil- cular mix of silt, sand, or clay, and binding with soil organic matter. Higher organic mat- ecause soil organic matter binds soil particles es that resist erosion. A region's climate influ- iow much precipitation falls and whether it glaciers. Topography matters as well; all other pes erode faster than gentle slopes. However, rates more runoff, and therefore more ero- over that protects the soil from erosion. This amount of rainfall does not simply dictate d can be a dominant erosion process in arid urbed soil, like agricultural fields. Biological vorms or human activities such as plowing, islope.

erosional processes are more or less impor- tend to dominate. When rain falls onto the soil or runs off over it; greater runoff leads ugh runoff accumulates, flowing sheets of ort soil, carving small channels, called rills, erosive gullies—the name for incised chan- cannot be plowed over. On steep slopes, n saturate soil enough to trigger landsliding.

Wind can pick up and erode dry soil with sparse vegetation cover. While many of these processes operate in a landscape, the dominant process varies with the topography and climate.

In the 1950s soil erosion researchers began seeking a general equation to explain soil loss. Combining data from erosion research stations they showed that soil erosion, like soil production, is controlled by the nature of the soil, the local climate, the topography, and the nature and condition of the vegetation. In particular, rates of soil erosion are also strongly influenced by the slope of the land and by agricultural practices. Generally, steeper slopes, greater rainfall, and sparser vegetation lead to more erosion.

Plants and the litter they produce protect the ground from the direct impact of raindrops as well as the erosive action of flowing water. When bare soil is exposed to rain, the blast from each incoming raindrop sends dirt downslope. Intense rainfall that triggers rapid topsoil erosion exposes deeper, denser soil that absorbs water less quickly and therefore produces more runoff. This, in turn, increases the erosive power of the water flowing over the ground surface. Some soils are incredibly sensitive to this positive feedback that can rapidly strip topsoil from bare exposed ground.

Below the surface, extensive networks of roots link plants and stabilize the topography. In a closed canopy forest, roots from individual trees intertwine in a living fabric that helps bind soil onto slopes. Conversely, steep slopes tend to erode rapidly when stripped of forest cover.

Soil scientists use a simple system to describe different soil layers—literally an ABC of dirt. The partially decomposed organic matter found at the ground surface is called the O horizon. This organic layer, whose thickness varies with vegetation and climate, typically consists of leaves, twigs, and other plant material on top of the mineral soil. The organic horizon may be missing altogether in arid regions with sparse vegetation, whereas in thick tropical jungles the O horizon holds most soil nutrients.

Below the organic horizon lies the A horizon, the nutrient-rich zone of decomposed organic matter mixed with mineral soil. Dark, organic-rich A horizons at or near the ground surface are what we normally think of as dirt. Topsoil formed by the loose O and A horizons erodes easily if exposed to rainfall, runoff, or high winds.

The next horizon down, the B horizon, is generally thicker than the topsoil, but less fertile due to lower organic content. Often referred to as subsoil, the B horizon gradually accumulates clays and cations carried down into the soil. The weathered rock below the B horizon is called the C horizon.

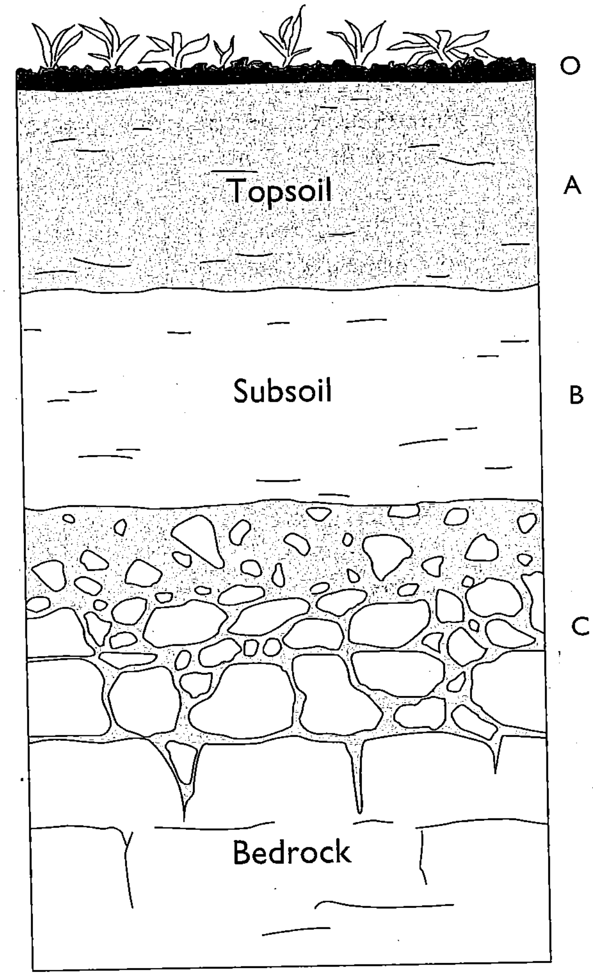
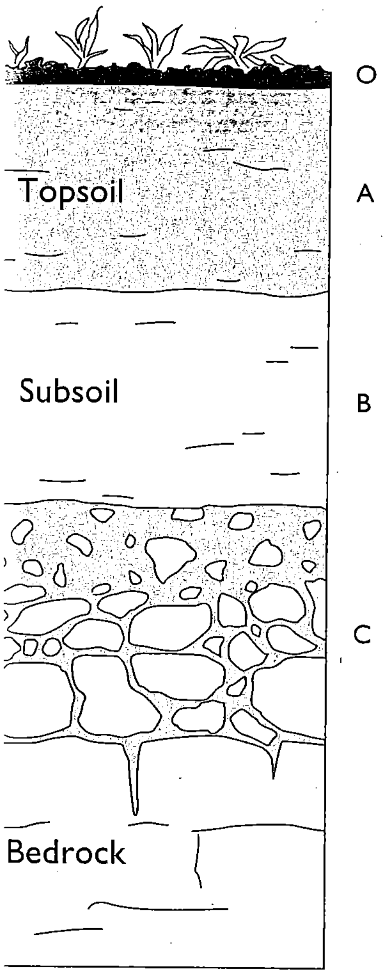


Figure 2. Over time, soils develop distinctive topsoil and subsoil horizons above weathered rock.

Concentrated organic matter and nutrients make soils with well-developed A horizons the most fertile. In topsoil, a favorable balance of water, heat, and soil gases fosters rapid plant growth. Conversely, typical subsoils have excessive accumulations of clay that are hard for plant roots to penetrate, low pH that inhibits crop growth, or cementlike hardpan layers enriched in iron, aluminum, or calcium. Soils that lose their topsoil generally are less productive, as most B horizons are far less fertile than the topsoil.



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Combinations of soil horizons, their thickness, and composition vary widely for soils developed under different conditions and over different lengths of time. There are some twenty thousand specific soil types recognized in the United States. Despite such variety, most soil profiles are about one to three feet thick.

Soil truly is the skin of the earth—the frontier between geology and biology. Within its few feet, soil accounts for a bit more than a ten millionth of our planet's 6,380 km radius. By contrast, human skin is less than a tenth of an inch thick, a little less than a thousandth of the height of the average person. Proportionally, Earth's skin is a much thinner and more fragile layer than human skin. Unlike our protective skin, soil acts as a destructive blanket that breaks down rocks. Over geologic time, the balance between soil production and erosion allows life to live off a thin crust of weathered rock.

The global geography of soil makes a few key regions particularly well suited to sustaining intensive agriculture. Most of the planet has poor soils that are difficult to farm, or are vulnerable to rapid erosion if cleared and tilled. Globally, temperate grassland soils are the most important to agriculture because they are incredibly fertile, with thick, organic-rich A horizons. Deep and readily tilled, these soils underlie the great grain-producing regions of the world.

A civilization can persist only as long as it retains enough productive soil to feed its people. A landscape's soil budget is just like a family budget, with income, expenses, and savings. You can live off your savings for only so long before you run out of money. A society can remain solvent by drawing off just the interest from nature's savings account—losing soil only as fast as it forms. But if erosion exceeds soil production, then soil loss will eventually consume the principal. Depending on the erosion rate, thick soil can be mined for centuries before running out; thin soils can disappear far more rapidly.

Instead of the year-round plant cover typical of most native vegetation communities, crops shield agricultural fields for just part of the year, exposing bare soil to wind and rain and resulting in more erosion than would occur under native vegetation. Bare slopes also produce more runoff, and can erode as much as a hundred to a thousand times faster than comparable vegetation-covered soil. Different types of conventional cropping systems result in soil erosion many times faster than under grass or forest.

In addition, soil organic matter declines under continuous cultivation as it oxidizes when exposed to air. Thus, because high organic matter content can as much as double erosion resistance, soils generally become more erodible the longer they are plowed.

Conventional agriculture typically increases soil erosion to well above natural rates, resulting in a fundamental problem. The United States Department of Agriculture estimates that it takes five hundred years to produce an inch of topsoil. Darwin thought English worms did a little better, making an inch of topsoil in a century or two. While soil formation rates vary in different regions, accelerated soil erosion can remove many centuries of accumulated soil in less than a decade. Earth's thin soil mantle is essential to the health of life on this planet, yet we are gradually stripping it off—literally skinning our planet.

But agricultural practices can also retard erosion. Terracing steep fields can reduce soil erosion by 80 to 90 percent by turning slopes into a series of relatively flat surfaces separated by reinforced steps. No-till methods minimize direct disturbance of the soil. Leaving crop residue at the ground surface instead of plowing it under acts as mulch, helping to retain moisture and retard erosion. Interplanting crops can provide more complete ground cover and retard erosion. None of these alternative practices are new ideas. But the growing adoption of them is.

Over decades of study, agronomists have developed ways to estimate soil loss for different environmental conditions and under different agricultural practices relative to standardized plots. Despite half a century of first-rate research, rates of soil erosion remain difficult to predict; they vary substantially both from year to year and across a landscape. Decades of hard-to-collect measurements are needed to get representative estimates that sample the effect of rare large storms and integrate the effects of common showers. The resulting uncertainty as to the relative magnitude of modern erosion rates has contributed to controversy in the last few decades over whether soil loss is a serious problem. Whether it is depends on the ratio of soil erosion to soil production, and even less is known about rates of soil formation than about rates of soil erosion.

Skeptics discount concern over erosion rates measured from small areas or experimental plots and extrapolated using models to the rest of the landscape. They rightly argue that real data on soil erosion rates are hard to come by, locally variable, and require decades of sustained effort to get. In their view, we might as well be guessing an answer. Moreover, only sparse data on soil production rates have been available until the last few decades. Yet the available data do show that conventional agricultural methods accelerate erosion well beyond soil production—the question is by how

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much. This leaves the issue in a position not unlike global warming—while academics argue over the details, vested interests stake out positions to defend behind smokescreens of uncertainty.

Still, even with our technological prowess, we need productive soil to grow food and to support plants we depend on—and our descendants will too. On the hillslopes that support much of our modern agriculture, soil conservation is an uphill battle. But there are some places where hydrology and geology favor long-term agriculture—the fertile river valleys along which civilizations first arose.