A WORLD WITHOUT SOIL

THE PAST, PRESENT, AND PRECARIOUS FUTURE OF THE EARTH BENEATH OUR FEET

• • •

JO HANDELSMAN

WITH RESEARCH AND CREATIVE CONTRIBUTIONS BY KAYLA COHEN

Yale UNIVERSITY PRESS

New Haven and London

Published with assistance from the Alfred P. Sloan Foundation Program in Public Understanding of Science and Technology.

Published with assistance from the Louis Stern Memorial Fund.

Copyright © 2021 by Jo Handelsman. All rights reserved. This book may not be reproduced, in whole or in part, including illustrations, in any form (beyond that copying permitted by Sections 107 and 108 of the U.S. Copyright Law and except by reviewers for the public press), without written permission from the publishers.

Yale University Press books may be purchased in quantity for educational, business, or promotional use. For information, please e-mail sales.press@yale.edu (U.S. office) or sales@yaleup.co.uk (U.K. office).

Set in Adobe Garamond type by Integrated Publishing Solutions, Grand Rapids, Michigan.
Printed in the United States of America.

Library of Congress Control Number: 2021935605
ISBN 978-0-300-25640-6 (hardcover : alk. paper)

A catalogue record for this book is available from the British Library.

This paper meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

10 9 8 7 6 5 4 3 2 1

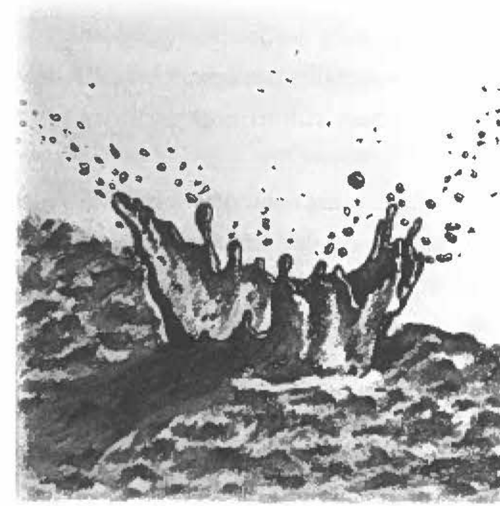
For John Nagy, and all the other farmers lineated by the last glaciation event in Wisconsin. On the east side of the line is a terminal moraine where the colossal slab of ice stopped, leaving behind deep deposits of rocks, gravel, and debris. On the west and unglaciated side of the dividing line, the soil is silty and soft. The border of the two affords a stark glimpse of events that occurred ten thousand years ago.

South of the glaciated regions, we find very different soils, including the Ultisols, which occur in warm, humid climates around the world. Silica, iron, and clay typically leach from the upper layers of these soils, bleaching them to gray or white. The particles are deposited in the lower soil profile, where they react with oxygen, forming the soft reddish or yellow color typical of metal oxides.

All of the Earth's soils tell a story of the past. It's up to us to write their future.

5

Wind, Water, and Plows



Today farmers around the world are grappling with erosion (see pl. 2). Instead of fertile O and A horizons, where the fertility and life largely reside, some farmers are left with only the subsoil or, worse, the rubble of rocky parent material. Others are just starting to see erosion nibble away at the topsoil and with it, productivity and profit.[1] For these farmers erosion is no abstract threat; it is a tangible loss of the primary resource upon which their livelihoods depend. Some are caught in a destructive cycle of land degradation, propping up yields with excessive fertilizer until erosion renders the land unproductive. Families are forced to abandon exhausted land and find new ground to grow their crops and feed their livestock. But erosion is not an inevitable outcome of farming. Many farmers maintain healthy soil, restoring the nutrients their crops and animals remove and preventing soil displacement. Some indigenous people have been doing this for centuries, and other communities are just discovering soil conservation practices. To guard soil for future food security and environmental stability, we need to understand good soil stewardship and adopt its practices more broadly. But first, it is worth delving into the nature of erosion. Let's start with its causes.

Erosion is a natural process caused by wind and water. It is as old as soil itself, chiseling the Earth's surface to its current splendor, creating the sinuous paths taken by rivers, revealing craggy outcroppings of some geologic relics and molding the graceful contours of others. Although its impact can be good or bad, erosion itself is neutral. When soil particles are detached and moved to a new location, we call it erosion. We often refer to soil "loss," but in reality, erosion means that soil is lost only from its original location. This usually means removal from agricultural settings where it is needed.

The impact on the places where soil lands can be either ruinous or enriching. Fertile soil may end up where it is useless to agriculture—in ditches, on roads, or buried under less fertile layers where it is inaccessible. Some settles in reservoirs, reducing their water-holding capacity by as much as 50 percent, and some clogs waterways, where its nutrients can be liberated to support overgrowth of hungry microbes that destabilize local ecosystems and suffocate aquatic life.[2]

In contrast, some deposition events are a boon to the local environment because they replenish and enrich local soil, delivering much-needed minerals to nearby fields or distant continents. This is an annual occurrence around rivers that flood their banks, distributing upstream soil onto adjoining land. The great deltas around rivers such as the Nile and the Mississippi form when rivers recede, producing some of the most productive agricultural land in the world.

If it has always occurred, what's the problem? Why are current rates of erosion troubling? At any location, soil depth is determined by the balance of soil genesis and deposition with the opposing force of erosion. The natural rate of topsoil production is at most 0.5–1.0 tonnes of topsoil per hectare per year. With a global annual erosion rate averaging 13.5 tonnes per hectare, there's a problem—*soil is vanishing from the locations where it was produced on average ten to thirty times faster than it is generated.* That's not sustainable! In many regions of the world, farming practices have accelerated erosion to a pace that endangers food security. Erosion is hastened further by climate changes that bring aggressive rainstorms and climbing temperatures that compound the effects of farming on soil. As the human population grows, farming intensifies, climate change worsens, and soil is the victim.[3]

The effects of unsustainable erosion are felt at every level, from personal to global. On farmland, erosion reduces crop yields and leads to more erosion, exacerbating farmers' financial hardship that follows. Erosion of some soils, especially peaty Histosols, often leads to transformation of soil carbon to greenhouse gases that warm the planet. Erosion's role in the global carbon budget is understudied and remains controversial, but as a consequence of the production of greenhouse gases that sometimes follows erosion, it may contribute as much as 2 gigatonnes of carbon to the atmosphere annually.[4] That represents around 20 percent of annual global emissions from burning fossil fuels. Some compensation for these gases is probably gained from eroded soil that is buried where it is deposited, reducing its potential for release of greenhouse gases.

What are the natural drivers of soil erosion? Erosion by wind is perhaps more famous than by water because windstorms dramatically obscure visibility and create patterns that can be observed from Earth or in images procured by satellites. Dry soil is especially susceptible to wind because dry particles can be dislodged more easily than those anchored by a film of water. Wind-generated forces, known as aeolian processes, deplete the contributing land and drive formation and enrichment of recipient soils around the world. Among the most vulnerable to erosion are the arid and semiarid soils, such as Aridisols and some Entisols, that cover 40 percent, or 430 million hectares, of the Earth's surface. The annual global dust emissions from drylands and deserts are somewhere between 1 and 4 gigatonnes, with more than half from North Africa. Winds whisk soil particles off the surface of the Sahara Desert and carry them far above the Earth to distant parts of the world. Incoming desert soil enriches phosphorus stores in South America's Amazon rain forest. Similarly, dust from Asia sustains Hawaiian land and can even reach the west coast of North America. The deposited minerals nourish American soil, but at the cost of depleting desert soils in Africa and China. Some of the same lands that receive soil gifts from other continents also suffer their own erosion. In the United States alone, wind erosion is estimated to remove 0.63 billion tonnes of soil annually, predominantly from dry croplands.[5]

Wind erosion events punctuate history. One of the worst dust storms in United States history struck on April 14, 1935. The date is remembered as Black Sunday because winds measuring 100 kilometers per hour tore through the Great Plains, sweeping almost 1 million tonnes of dry topsoil into the air, blotting out the sun in Oklahoma. Black Sunday marked the midpoint of the Dust Bowl decade, a drought spanning the 1930s, which was studded with windstorms

that removed massive amounts of the mighty Mollisol, the foundation for agricultural productivity in the United States. Years of poor land management, such as heavy tilling and planting soil-depleting crops year after year, had left the Plains soil vulnerable to wind erosion.[6]

Wind erosion is the leading cause of desertification in northern China, turning fertile soil into arid land. Although wind erosion has sculpted much of China for centuries, and dust storms have been documented since 205 BCE, during the past seventy years soil loss has heightened, making the Gobi the fastest-growing desert in the world. More than 70 million hectares have been degraded, most of them now infertile. Close to 30 percent of China's desertified land is used for livestock and crop production, which amplify its vulnerability to erosion.[7] Affected farmers sometimes buttress crop production with high fertilizer application, but this is a temporary fix for yield, and it spawns environmental problems such as pollution of waterways and production of nitrous oxide—a potent greenhouse gas. Moreover, when farmers boost yields with excessive fertilizer that masks the impact of erosion, they may be less likely to address soil loss, which may be catastrophic for their soil in the longer term.

India is known for its regular dust storms, but in 2018 a particularly powerful storm ravaged the northern states of Uttar Pradesh and Rajasthan. High-velocity winds arrived before the rainy monsoon season began, so the soil was dry and erodible. Trees and utility poles were ripped from the ground and buildings fell, taking more than one hundred human lives. India's repeated dust storms, which cause erosion, air pollution, lung disease, eye damage, and loss of human life are thought to result from poor soil management practices in agriculture coupled with drought and severe winds (fig. 8). But as much as it erodes soil, wind is responsible for only 18 percent of the total erosion on India's impressive 180 million hectares of agricultural land; the rest is caused by water.[8]

Figure 8. Dust storm. Illustration by Helen Jones.

Compared with the dramatic effects of wind, erosion by water is often less visible but far more pervasive. In fact, water is the most prevalent earth mover worldwide, detaching particles from the bulk soil and propelling them into rivulets, gullies, and streams (see pls. 3 and 4). Water meets soil through flooding, irrigation, and rain events, which are particularly important because of the force with which raindrops hit the ground. Individual raindrops may seem gentle, but their collective power is literally earth-shattering: 100 centimeters of rain pummeling the surface of 10 hectares deliver the kinetic energy equivalent of 1 tonne of TNT explosives. To a clod of soil, rain can be cataclysmic. Worldwide, water is thought to remove 20–50 billion tonnes of soil annually from its original location.[9] This is expected to increase as climate change intensifies, bringing more severe rainstorms to locations around the world.[10]

Water erosion is most destructive on sloped land where gravity pulls water to lower elevations, sweeping the soil along with it. The steeper or longer the slope, the greater the potential for water erosion. The resultant changes to the landscape range from imperceptible to total remodeling, where small rills or great gullies serve as highways for soil moving across the landscape slowly or rapidly depending on slope, obstacles, and water depth (fig. 9). Soil eventually settles in lower positions on the landscape or continues on its journey into culverts, reservoirs, streams, rivers, and the sea, where it may help or hurt the local ecosystem.[11]

Water falls unevenly across the globe, but its erosive power does not discriminate. In Africa south of the Sahara, water erosion is estimated to have degraded 46 percent of the land, including 80 percent of Nigeria. On the volcanic islands of the South Pacific, the steep topography and intense storms conspire to cause average erosion of 50 tonnes of soil per hectare per year, which is exacerbated in Papua New Guinea and the Solomon Islands by deforestation that has left the soil vulnerable. In India, water plays many roles, good and bad. Although the country suffers from chronic water shortages, water has eroded soil from more than ninety million hectares, or one-third of India's total land. Between 1950 and 2008, India more than tripled its irrigated land area, which has boosted food production to unprecedented levels but has also damaged soil by salination—a process that brings salt dissolved in groundwater to the surface, where it accumulates. At high levels, these salts stunt plant growth, making the plants less supportive to soil production and ultimately heightening erodibility.[12] Water issues challenge India's ability to remain food self-sufficient, which will demand almost doubling agricultural production from 2006 levels to feed the population of 1.62 billion people projected to inhabit India by 2050. A growing population cannot be sustained easily on a shrinking fertile landmass.

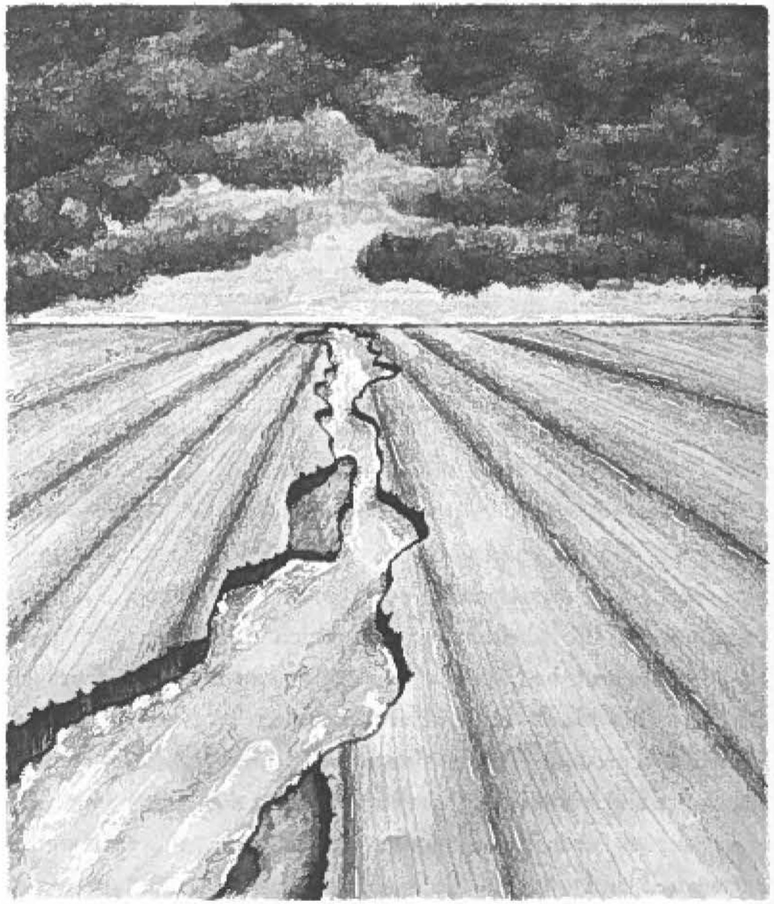


Figure 9. Eroding rill on an intensively farmed field. Illustration by Liz Edwards and based on a photograph by Katharina Helming.

Critical to conclusions about erosion is the ability to estimate it accurately. Tracking the journey of soil from where it is dislodged to its resting place has never been an easy task. Farmers have undoubtedly observed soil move from their fields or accumulate elsewhere

since the beginning of agriculture. Casual observations document erosion before it was studied formally. For instance, an investigation of Russia's Svir River in 1897 estimated that a meter of soil had been deposited in the river throughout the previous century based on the depth of hundred-year-old coins found buried in the river's sediment. But until the twentieth century erosion had scarcely been measured systematically. In 1915, Ray McClure, an undergraduate student at the University of Missouri, set out to study nutrient loss in runoff water from agricultural fields. While conducting his research, McClure asked his adviser how his measurements should handle the sediment that was carried in the runoff water from high to lower ground. The professor advised him to measure the sediment and nutrients in it, and McClure found that the nutrient levels in the runoff water and displaced soil were greater than the amount of fertilizer that had been applied to the fields, indicating a net loss of nutrients from the fields. His research also quantified the amount of soil lost from the fields, and thus began the study of soil erosion in the United States.[13] His investigation also illustrates the important property of erosion: displacement from a point of origin. In McClure's case, he could measure the accumulation of the soil down the hill from where it was dislodged. In many cases, the moved soil is as good as lost to its original landlord because it is buried in another field, spread across roads, blown to another continent, or washed into waterways.

Since McClure's experiments, the study of erosion has become more sophisticated. For decades, soil scientists have been estimating the rate of erosion from agricultural land using five methods. None is perfect, and each needs to be used with consideration of sufficient sampling and appropriate comparisons. They are:

Soil depth. We can measure the thickness of the surface layers of soil. Some researchers measure the depth from the surface to the soil's parent material. Others use the depth from the surface to the base of the A horizon, focusing on the portion richest in organic matter and excluding subsoil. The location of the subsoil and parent material doesn't change over time, so the distance from the surface to these layers indicates the amount of soil overlaying the mineral substrate. To estimate how much has been lost since the beginning of cultivation, we can compare the soil depth on an agricultural field against a nearby uncultivated area where the soil depth is likely similar to what it was when the land was converted to agriculture. Even better, repeated measurements of the same location can estimate soil loss over time. In a powerful application of soil depth comparisons, Jessica Veenstra and Lee Burras at Iowa State University assessed the impact of continuous row-crop agriculture over fifty years. They used data from a 1959 soil survey that described soil profiles at eighty-two sites representing twenty-one Iowa counties and compared them with profiles taken at the same locations in 2007. The thickness of the top horizon diminished on average from 15 to 1 centimeters across the eighty-two sites, and the hill bottoms accumulated soil. The eroded soil lost its aggregate structure during transport, rendering it far less healthy than it was in its original location. The study indicates that the top horizon shrank by 90 percent in forty-eight years. The plant roots were experiencing a very different, and less fertile, soil environment in 2007 than when the first samples were collected in 1959.[14]

Runoff or sediment. Soil erodes from one place to another, so we can estimate erosion based on the amount removed from one location or accumulated in the other. Researchers can estimate soil leaving a site by placing soil of a known weight in a mesh bag and measuring loss over time. By placing bags at enough locations across a field and validating the results with another method (such as runoff measurements), scientists can obtain a reasonable estimate of soil loss. To measure runoff at the point of deposition, they can install a vessel downslope from the field of interest to catch the soil that runs off the field.

Gutters or other containers can be used to collect the soil at intervals across the lower area. The weight of soil that accumulates in the vessel is measured over time, and averaging across collection units provides an estimate of soil erosion per hectare per time period. One study found that estimates of soil loss and downslope accumulation on the same fields were almost identical, indicating that these methods were likely measuring the same process and providing some confidence in the estimates. Long-term trends are measured through sediment accumulation in reservoirs and other bodies of water, but these measurements grossly underestimate erosion because less than half of eroded soil typically ends up in the water. Sediment collection in waterways is particularly powerful when used to compare the impact of management practices on the land that generates the sediment. In a study conducted by Wayne Erskine's group in New South Wales, Australia, researchers used a series of small dams to collect soil eroded from upslope land. The dams below cropland collected triple the amount of soil as those below forestland, indicating the erosive impact of cropland management. Even if the absolute amount of sediment collected underestimates erosion, comparing the relative quantities among different land management regimes is meaningful.[15]

Radioactive isotopes. Before the 1996 ban on nuclear testing, the United States, former Soviet Union, and several other countries conducted more than two thousand tests of nuclear weapons. Five hundred were nuclear bombs detonated aboveground that spewed radioactive byproducts into the atmosphere, some of which were eventually deposited on soil across the world. Similarly, the explosion in 1986 of the nuclear facility at Chernobyl in Ukraine and other nuclear accidents released radioactive fallout that settled on soil across the world. Soil particles rapidly bind radioactive elements, anchoring them in place and making the soil surface more radioactive than deeper layers. As the soil erodes from the surface, the radioactivity diminishes in its original location, providing an estimate of soil loss. Researchers have validated the radionuclide method by calibrating it with direct measurements of sediment accumulation and soil redistribution. The measurements are most useful when comparisons are made to baseline values at initial time points or compared with patterns of radioactivity on the surface of uncultivated land. The accumulation of radioactivity can also be used to determine the path of erosion and points of soil deposition. A second method, using radioactive beryllium, is used primarily for estimating erosion in geologic time or before human intervention. Radioactive forms of beryllium are relatively rare in the Earth's crust. They are generated by cosmic rays impinging on the Earth's surface and thus can be used to trace what was once surface soil in sedimentary rock layers.[16]

Remote sensing. The launching of the first satellite into space in 1957 gave us an entirely new view of our planet. Satellite images, or remote sensing, have proven useful for assessing soil moisture, roughness, vegetation, and topography. The images created from visible or infrared light reflected from the Earth's surface are used to assess features of soil. The characteristics that affect water infiltration into the land, such as presence or absence of a soil crust, porosity, moisture, and plant residue or canopy, can be detected on satellite images. The process of desertification has been monitored, and soil management practices, such as tillage (which affects the roughness) and cover cropping (based on exposure of bare soil) can also be observed. Large gullies can be directly detected, as can soil in waterways, because water's reflectance of visible and infrared light is increased by suspended sediment. The power of satellite imaging lies in the large land area that can be surveyed and how frequently it can be measured. The United States launched its first Landsat satellite in 1972 and its eighth in 2013. Landsat 8 orbits Earth every ninety-nine minutes at an altitude of 705 kilometers, and in sixteen days it captures the entire Earth's

surface. Satellites also provide a historical record of soil erosion. In 2020 researchers assessed erosion in Slovakia over time using remote sensing images from 1949 to 2011.[17] Satellite data also democratize science—information gathered by Landsat is made available on three U.S. Geological Survey websites, so that eventually anyone will be able to track changes in soil.

Modeling. Soil scientists started correlating direct measurements of erosion with environmental factors in 1940 when the first quantitative relation between the slope of the land and erosion was established. The next association was between rainfall and erosion, established with measurements on approximately eight thousand plots. In 1965, several parameters were linked to erosion in a single mathematical model—the universal soil loss equation, or USLE, which computes the effects of rainfall, soil erodibility, slope length and gradient, and crop and soil management practices to estimate sheet and rill erosion (uniform removal of the surface layer of soil or transport of soil through channels, respectively). USLE was initially developed based on data from ten thousand measurements and has been validated with many more thousands of data points over the last six decades. The USDA's triennial Natural Resource Inventory reports soil erosion for every state using USLE. A significant limitation of USLE is its inability to account for erosion in gullies—the ephemeral deep cuts in land where masses of soil can wash away during storms; thus, in areas plagued by gully washes, USLE substantially underestimates erosion.[18] It is also limited by insufficient data in many locations, forcing the equation to use averages across large scales of time and space.

A second modeling approach, that of process-based estimates, is exemplified by the water erosion prediction project, or WEPP, which uses the processes of hydrology, plant growth, hydraulics, and erosion mechanics to integrate measurements of four factors—precipitation, topography, soil characteristics, and land use—into a sophisticated computer simulation of erosion. Whereas USLE correlations are based on static measurements that are correlated with past outcomes to estimate erosion in new settings, WEPP uses physical processes to integrate information into a prediction. Moreover, WEPP has the capacity to integrate satellite and other remotely sensed data collected frequently and at a granular spatial scale, providing a detailed portrait of continually changing weather and landscape. Integrating physical processes with rich data sets that capture the variation of terrain, weather, and farming practices across space and time makes WEPP erosion estimates applicable at many scales, including small fields to large watersheds. In an erosion project of unprecedented scale and accuracy, Professor Rick Cruse, with Research Manager Brian Gelder and their team at Iowa State University, has harnessed the power of WEPP to model erosion across Iowa in the Daily Erosion Project. The project is identifying locations prone to particularly high or low levels of erosion to enable interventions and understanding of the erosion process. Its utility is now broadly recognized, leading to its implementation beyond Iowa.[19]

All methods for estimating erosion are imperfect. Insufficient sampling can produce faulty conclusions with any of them. Some account only for soil movement from a location, others only its arrival to a new location. Geologists, for instance, tend to focus on measuring sediment in waterways, which is usually less than the amount of soil displaced from fields. The discrepancy between measurements of soil lost and sediments accumulated in waterways has led several geologists to suggest that the soil measurements overestimate erosion. But most critics do not account for the soil that is lost from agricultural fields and buried downslope, transported to a ditch, or diminished by transformation of organic matter to greenhouse gases. These all represent sources of soil that is eroded, is not available for

agricultural production, and does not appear as sediment in waterways. Combining USLE with radioactive tracking and data from satellite images has helped to corroborate conclusions from each approach.[20]

Inaccessible and remote areas present an additional problem for generating accurate estimates of soil loss worldwide. Some erosion estimates in these regions have incorporated on-site information from farmers or researchers, but others rely entirely on remote sensing and GIS-based measurements. And the mountainous areas that are often hardest to reach are also where erosion is most severe.[21]

A big challenge to making sense of soil erosion is that it is reported as average rates across large land areas, but averages obscure local trends, which can be far higher or lower than the average. Erosion varies dramatically at different scales and across the globe. For example, although the global average of 13.5 tonnes per hectare per year might not immediately raise an alarm, contributing to that average is Fiji, a land losing soil at the fast clip of 50 tonnes per hectare annually. Likewise, annual erosion on cropland averages approximately 10 tonnes per hectare in the United States and 13 tonnes per hectare in the state of Iowa—rates similar to the global average. But in 2007, 2.4 million hectares in Iowa suffered losses of twice the state average. On May 6 of that year, 4 million hectares lost as much soil as is usually lost in an entire year, and 80,000 hectares lost 220 tonnes per hectare *in one rainstorm,* a loss more than one hundred times the soil renewal rate. After twenty such storms, a typical hectare of Iowa farmland endowed with 2,200 tonnes of soil will not have much remaining. In fact, about 4–17 percent of Iowa is in landscape positions most prone to erosion and for the most part devoid of topsoil, exposing geologic parent material (see pl. 6, top). So although the average for the United States or the state of Iowa might not be alarming, local loss may be more severe, rapidly stripping the soil and reducing productivity. In 2021 a shocking study revealed that across the Corn Belt of the United States about one-third of the agricultural land has already lost all of its topsoil.[22]

Since the beginning of agriculture, people have been accelerating erosion, whether we knew it or not. Thomas Jefferson, the third president of the United States, was a distinguished statesman, farmer, and architect. He was also a mass of contradictions. He wrote the Declaration of Independence, a brilliant tribute to human will and individual agency, yet he owned slaves throughout his life. He sought political counsel from Abigail Adams, wife of the second president of the United States, and yet he believed that women's only destiny was to serve men and raise children. He was also a scientific farmer, conducting extensive experiments to manage his 12,500-hectare plantation at Monticello, Virginia. Jefferson fervently believed in good land stewardship and yet spent five years inventing a new version of the moldboard plow, which has arguably caused more soil loss than any other implement in the history of agriculture (fig. 10). In 1813, Jefferson wrote in a letter that "the plough is to the farmer what the wand is to the sorcerer. It's [sic] effect is really like sorcery." And he pronounced deep plowing "a recipe for almost every good thing in farming."[23] As we'll see, he was colossally wrong!

Plows have been used since 3500 BCE to break ground for planting seeds. On uncultivated land, vegetation can be dense and difficult to penetrate with hand tools. The invention of the plow, which was originally made entirely of wood and pulled by animals, opened more of the Earth's surface to agriculture, thereby advancing the spread and productivity of agrarian societies. The moldboard was added to the plow to cut deeply into the soil, lifting and flipping it over 180 degrees. Jefferson's moldboard was made of iron, designed to be easier than its wooden predecessors for a horse to pull.

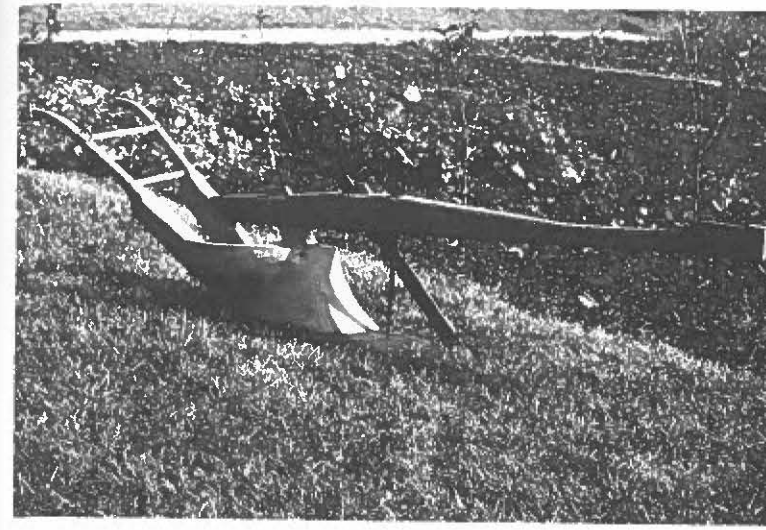


Figure 10. A modern recreation of Jefferson's "mouldboard plow of least resistance." Photograph printed with permission from © Thomas Jefferson Foundation at Monticello.

When agriculture moved west, farmers found that the iron plow didn't work as well as it did in the East. Designed for eastern soils, it rapidly became caked with the heavy midwestern soil, forcing farmers to stop every few meters to clean it. In 1837, a blacksmith named John Deere invented the first steel plow, which was heralded as a great advance because soil did not stick to the steel blade, and it was stronger than iron, enabling farmers to break ground that was previously thought unfarmable (fig. 11).[24] Deere built ten moldboard plows in 1839 and one hundred by 1842, creating the John Deere Company, a global farm implement business that still carries his name today.

Jefferson was partly right about the importance of the moldboard plow because it made the United States the agricultural powerhouse it is today. The capacity of the steel plow to break tough land expanded crop production across the Midwest and Great Plains in the nine-

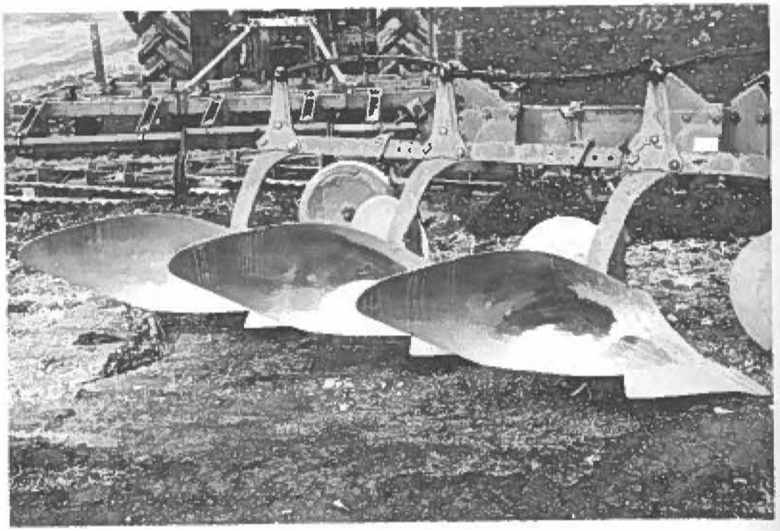


Figure 11. A modern moldboard plow. Photograph by Dwight Sipler.

teenth century. The agriculture that sprang from the newly opened earth also opened the rest of the United States to development, industrialization, and the many cultures that arrived with migrants exploring the western reaches of the continent.

The plow also had tragic consequences. It enabled droves of European settlers to move west where they displaced millions of indigenous people who had lived on the land for centuries. It also caused loss of much of the Midwest's soil and likely more than 25 percent of its carbon over the ensuing two hundred years.[25]

The plow became more than the tool of choice for breaking new ground. Its role grew to include turning cultivated soil every spring for planting, disrupting soil between crop rows to suppress weeds, and burying crop debris after harvest. Repeated tilling can cause erosion by directly moving soil downhill or off fields, but its greatest impact

is the destruction of soil architecture, breaking clods into small particles vulnerable to movement by wind and water.

What prevents erosion? Plants are potent antidotes to soil movement. Hedgerows and wind breaks reduce wind velocity across cultivated fields. Trunks and stems hinder flow of rivulets, increasing the chance that water will penetrate the soil rather than run across its surface. Leaf canopy reduces the velocity of raindrops, which gently drip into the soil from the leaves that intercept them. Below ground, roots provide channels for the downward movement of water. Soil structure and water-holding capacity are improved by strands of glues produced by plants and bacteria that bind particles. Most plant species contribute to soil health, but the majestic giants of the world's forests are champions at soil protection. Their roots form immense subterranean networks that nourish the soil and anchor it to the terrain beneath.

Imagine, then, the impact of clear-cutting forests such as the tropical forests in the Amazon and Indonesia that are destroyed at a rate of approximately one football field per second, all day, every day. Societies throughout history have replaced forests with farmland to grow food and build shelters, but on sloped land the results can be calamitous if agricultural practices have exposed the soil to erosive forces. Several civilizations have collapsed or been forced to abandon their land after suffering widespread soil loss that resulted from deforestation.[26] Soil may be lost from denuded land gradually over centuries or rapidly over decades, depending on the quality of the initial soil, the slope of the land, the weather, and farming practices. Those agrarian societies that have persisted successfully on steep, formerly forested land are accomplished land stewards who have found ways to anchor the soil in place.

In the United States, deforestation began centuries ago. The stark consequences are evident in the Piedmont region that was clear-cut for farming. The Piedmont starts in New York State, spans Virginia and North Carolina, and extends into Georgia and Alabama. The region is not fit for agriculture without soil protection. Its steep and rolling hills are remnants of ancient mountain ranges of acid igneous rocks that spawned thin, sandy soils, carrying a mere 6–10 centimeters of topsoil. The forests had held the soil and fragile ecosystem in place, but from its settlement by Europeans in 1700 through the 1970s, the trees that were anchoring Piedmont soil were steadily replaced with fields. Plowing disrupted the soil, and crops such as tobacco sapped nutrients. Over time erosion on agricultural land increased one hundredfold compared with uncultivated areas of the Piedmont hills, eventually stripping most of the topsoil. Once the eastern Piedmont land became marginal, the settlers moved farther west to clear more forests for agriculture. Waves of migrants fled first to the middle Piedmont and then to its western edge in Georgia and Alabama in search of fertile soil. By 1967 Piedmont farming had largely ceased because the soil no longer supported it. By the end of the twentieth century the region had largely degenerated into scrub.[27]

The Piedmont may presage the outcome of erosion that is in progress across the United States and many other parts of the world. Europeans settled in the Midwest long after the Piedmont region, so the damage done by European Americans' agricultural methods appeared later. For example, in 1850 Minnesota's population was six thousand, whereas Virginia's population had surpassed that mark two hundred years earlier. Moreover, Midwest topsoil is deeper than Virginia's. So it is not surprising that the kind of wasteland soil evident in the Piedmont is rare in the Midwest. But Minnesota's erosion is estimated to have increased one hundredfold since arrival of European settlers, suggesting that its trajectory may be similar to the Piedmont's, just delayed. With estimates of global soil loss due to agriculture between 75 gigatonnes per year and more than 130 gigatonnes per year (exceeding the rate of soil genesis by thirty-seven to sixty-five times), it is likely that many other regions are following the pattern of the Piedmont.[28] Another pattern that is recapitulated across the globe is that exhausted soil leads to the abandonment of land, followed by human migration.

The Piedmont's agricultural history also shows us that the transition from perennial to annual plants can ravage the soil. In this case, planting annual row crops such as cotton and tobacco sacrificed the ancient, sprawling root systems of the perennial trees they replaced. The life strategies of annuals and perennials differ in that annuals complete their lives in a single season, and perennials go dormant in the winter and then grow again in the spring. Annuals reproduce only through seed, whereas perennials' resilient roots persist from year to year, giving them renewed life each spring in one location while their seeds spread them to others. To maximize the potential of each life strategy, at the end of the growing season annuals dedicate their photosynthetic resources to creating seeds that will serve as their genetic legacy, whereas perennials invest energy in their roots—the organ that gives them life in the next season. Deforestation is just one practice that forfeits the underground influx of gifts from perennial plants that give soil its robust structure and nourish its inhabitants.

Like deforestation, the conversion of prairies to agricultural crops has replaced perennial with annual plants. Not surprisingly, this is another kind of land use that has accelerated erosion. The vast expanses of prairies and steppes that once covered almost 2.5 billion hectares of the world's fertile, black Mollisols were home to hundreds of perennial plant species, which annually flaunt their diversity above ground as an indicator of the industry going on below.[29] It is the root systems of these plants that make possible the spring-through-autumn pageant of flowers: the pink sweep of prairie shooting stars followed by expanses of majestic blue lupines, the sizzling orange Indian paintbrush, the charming yellow cup flower, and hundreds of others. The delicate tassels of perennial grasses dance in summer breezes before their foliage turns shades of brown and purple as the plants begin to prepare their roots for winter. The aboveground prairie beauty is a colorful celebration of the powerful root systems that hoard nourishment to survive harsh winters and return to active duty in the spring.

The roots of perennial grasses and legumes are often larger than their stems, leaves, and flowers—an underground cache that expands each year. The roots of perennial grasses such as switchgrass, for example, contain 50 percent of the plant's biomass during its first year of growth, and by the third year the roots have outstripped the shoots to garner 80 percent of the plant's biomass, extending more than 4 meters down the soil profile. Perennial roots also turn over rapidly, with 30–86 percent replaced each year.[30] The decomposition of this prodigious underground filigree forms deep soils containing copious organic matter that have provided abundant harvests around the world. Now these prairie soils are under threat.

Because plants have a finite amount of carbon to distribute to their organs, abundant seed production is often associated with diminutive root systems (fig. 12). When people started breeding annual crop plants to optimize seed production, their roots shrank further. Today the roots of a typical corn or wheat plant represent only 40 percent of the plant's biomass during the growing season and as little as 3 percent by harvest, leaving a trifling amount of carbon to restock the soil. In the United States 99 percent of the original prairies are now used for agriculture, including much of the nation's 225 million hectares of corn and 157 million of wheat.[31] It was this conversion that led to the Dust Bowl.

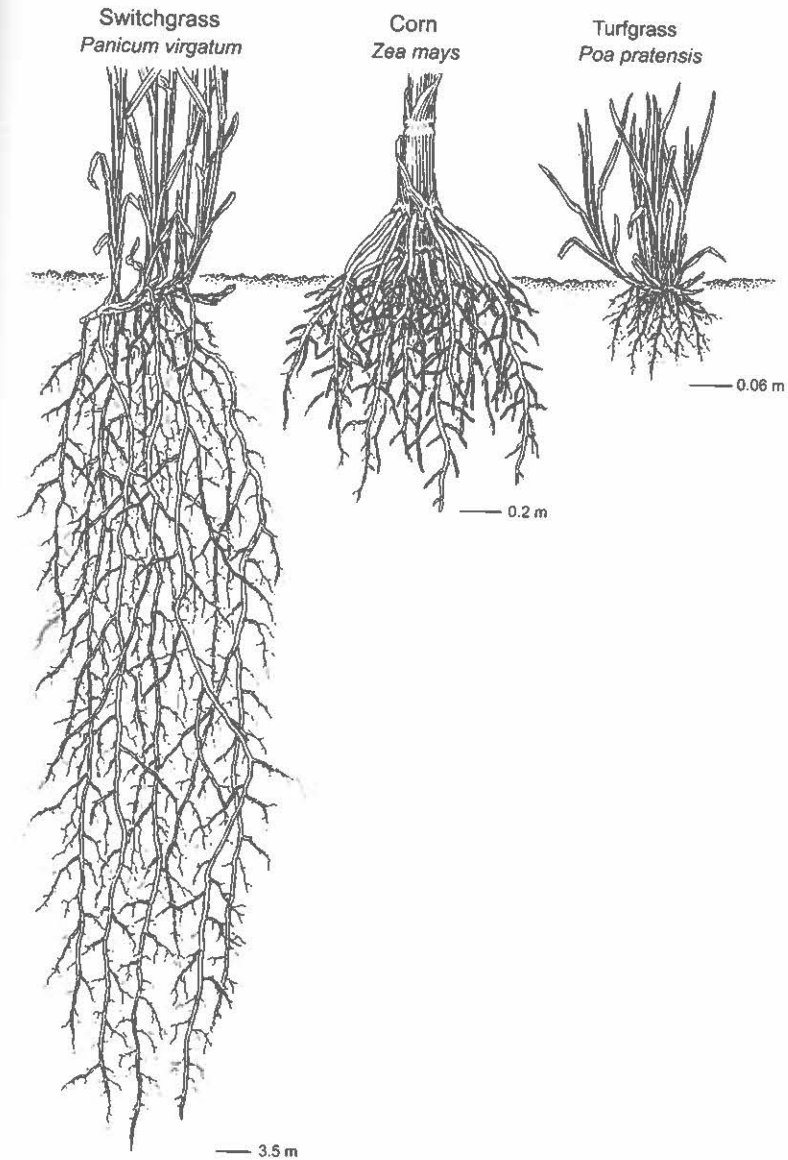


Figure 12. Roots of a prairie perennial plant (switchgrass) and domesticated corn and turfgrass. Illustration by Bobbi Angell.

The decline of the Piedmont region and the devastation of Oklahoma and Kansas during the Dust Bowl era bring into sharp relief contrasting causes of soil erosion. The Piedmont started with thin, forested soils that were diminished by deforestation and the cultivation of dense row crops. The steep slopes heightened the land's vulnerability to water erosion, and without trees, the fragile topsoil was rapidly washed away. In contrast, the plains of Oklahoma and Kansas are flat, but the transition from perennial prairie plants to annual crops made the soil susceptible to forceful winds during the drought of the 1930s. These erosion tragedies tell the same story. No matter whether topography or weather was the inciting factor, the decline of the soil in both instances can be attributed to the conversion of wild perennials with undisturbed soil to annual crops with meager root systems and ravaging deep soil plowing.

Given that the Virginia portion of the Piedmont area had already suffered extensive soil degradation by the time Jefferson invented his iron plow, it is surprising that a scientist with his commitment to land stewardship did not realize the impact of plowing on soil loss. In the same letter in which he extolled the virtues of the plow, he advocated reducing erosion by planting across hillsides rather than up and down them, a soil-protective practice known today as contour farming. But he stubbornly continued to believe that his plow was an entirely good thing for the land and even blamed "evil" rain for carrying soil off the land.[32] Whether or not Jefferson was aware of the connection, now it is well established that frequent land cultivation, particularly with a moldboard plow, hastens erosion. Today Jefferson's legacy is deeply tarnished by his slave-holding throughout his life. Less broadly appreciated is how his iron plow enabled European Americans to farm and populate the Midwest, thereby contributing—along with political, economic, and military objectives—to the devastation of many Native American populations and the destruction of the region's soil structure, paving the way for the Dust Bowl one hundred years later.

Cultivating crops is not the only way that agriculture erodes soil. Cattle and other hooved farm animals can completely transform the landscapes they traverse, degrading soil in several ways. When they are allowed to overgraze, livestock consume foliage down to soil level, dislodge plants, and prevent regrowth. Heavy animal traffic compacts the soil so that water cannot easily penetrate. Over time, plant growth is diminished, and the soil becomes drier and more erodible. Water scarcity, dwindling vegetation, and erosion become locked in a negative feedback loop that causes a spiraling ecosystem decline.[33]

People have been constructing edifices for a long time, but buildings began to have noticeable effects on soil in the twentieth century, especially as modern cities expanded. The drive toward urbanization is reducing the amount of land available for agriculture at a rate of 1.6–3.3 million hectares per year—that's the equivalent of the area of Lebanon and Belgium, respectively.[34] The choice of construction materials is also consequential. Impenetrable concrete and asphalt, for example, leave water without a route into the ground, which leads to flooding and soil erosion.

Of all types of construction, none has such visible impacts on soil as damming rivers. Rivers and dams exemplify the paradox of erosion as a benefit and a curse. Although upstream erosion may deplete the land, rivers often deposit silt on their banks and at the coast where they spill into the sea, thereby creating fertile floodplains and preventing shoreline erosion. But today, these processes are threatened by thousands of dams across the world.

Between 1960 and 1970, the Aswan High Dam was built to regulate the flow of the longest river in the world.[35] The majestic Nile traces a south-to-north trajectory through more than half of the African continent. Originating in Burundi, the White Nile River snakes north through Uganda, South Sudan, and Sudan. There it meets the Blue Nile River, sourced in Ethiopia. The two rivers merge to become the Nile River, which continues through Egypt, concluding its journey on Africa's northeastern coast, where it opens its massive mouth and flows into the Mediterranean Sea. Water from the Burundi source will take three months to reach the sea, traversing a 6,695-kilometer path, at times flowing gently, at others roaring along at 3 meters per second. The Nile erodes lands as it flows, collecting silt that it redistributes to the Nile Delta—the 20,000-square-kilometer region flanking the river—during floods, and to the coastline as it empties into the Mediterranean.

The purpose of the Aswan High Dam was twofold: to prevent the floods and droughts that plagued farmers in the Nile Delta and to provide hydroelectric power to the Egyptian people. Designed by a group of British engineers and built by a Russian team, the Aswan High Dam is a towering testament to human ingenuity. The dam—a rock and clay wall—stands 111 meters high and 3,830 meters across. It impounds 169 billion cubic meters of water that form a reservoir, Lake Nasser, which collects above the dam and extends 320 kilometers upstream in Egypt and another 160 kilometers in Sudan.

The Aswan High Dam accomplishes its intended tasks proficiently, discharging water at a measured cadence and generating 10 billion kilowatt-hours of electricity annually, enough to serve almost half of Egypt's population. But it also caused an unintended consequence. When the river reaches the Aswan High Dam, the flowing water comes to a halt, pooling in Lake Nasser. As the water is waiting to be released, it is stilled. Without the river's turbulence keeping silt particles suspended, they settle to the bottom of the lake. As a result,

98 percent of the silt does not traverse the dam, remaining in the reservoir and not deposited along the rest of the river. The Nile once made an annual delivery of 10 million tonnes of sediment to the surrounding delta on its way to the sea and 124 million tonnes when it reached its destination, the Mediterranean Sea. Today that sediment never reaches the riverbanks and ocean shorelines, leaving them without reinforcements to combat their own erosion. The downstream sediment deficit is causing the Nile's banks to recede, some at a rate of 125–175 meters per year. Likewise, the Mediterranean shoreline where the Nile empties is retreating rapidly.[36]

The dam has also starved the Nile Delta, source of two-thirds of Egypt's food production. The farmland now requires chemical fertilizers to replace the 7,000–10,000 tonnes of phosphorus, 7,000 tonnes of nitrogen, and 110,000 tonnes of silica once contributed by the Nile floods.[37] Some experts argue that the Nile no longer has a true delta because of the deficit of silt.

The Nile is not alone in its dam plight. Most of the world's great rivers have been dammed—the Amazon River, Yellow River, Columbia River, Colorado River, the River Tigris—either to regulate water flow or produce hydroelectric power. Each dam has had complex impacts on the land and people around it. Across the world, human intervention has increased sediment flowing through rivers by 2 gigatonnes and simultaneously reduced the amount reaching the coast by 100 gigatonnes because most of the sediment is trapped in dams. Today, silt fills one-fifth of the storage capacity, or 1,100 cubic kilometers, of the world's reservoirs above the dams and costs $2–$3 billion worldwide for repairs to damaged turbines and loss of power generation in hydroelectric plants.[38] Some have caused landslides, many have permanently altered agriculture downstream, and all have created both challenges and opportunities for local wildlife.

From the first dam in human history (the Jawa Dam in Jordan, built around 3000 BCE) to the first hydroelectric dam (built in Appleton, Wisconsin, in 1882) to the largest dam in history (the Three Gorges Dam on the Yangtze River in China, completed in 2006), each served a critical function for people, and all have altered the surrounding landscape. As with most technology, society needs to weigh the benefits of these wonders of engineering against their alterations of the natural world. The soil should receive consideration in this calculus.

Climate is a hybrid of natural and unnatural forces that drive soil erosion. Although climate events accompanied by high-velocity wind and water have always driven erosion, today the climate has taken a sharp, unnatural turn amplified by human activity. If climate is a natural driver of erosion, then anthropogenic climate change is an unnatural manifestation that is devastating soil. The effects vary by region. Some already suffer severe soil loss, and others will feel the effects in the near future. All indicators point to an increase in water erosion resulting from severe rainstorms that will become more common around the world. The more severe the storm, the worse for soil, because high-velocity raindrops carry the force needed to detach and move particles. The frequency of severe storms escalated in Asia, Europe, the Northern Territory of Australia, and North America between 1964 and 2014. This trend is strikingly apparent in U.S. records: for the first half of the twentieth century, the annual number of heavy precipitation events clustered around a mean, but since the 1950s, the frequency has steadily, unrelentingly risen (fig. 13).[39] The timing of these storms determines their impact. Early and late in the season, if the soil has been plowed but not yet planted, there are few barriers to soil movement and nothing to impede the raindrops. In the middle of the season, when crops are thirstiest and protect the soil, severe rain can be less damaging. But if the storm produces hail,

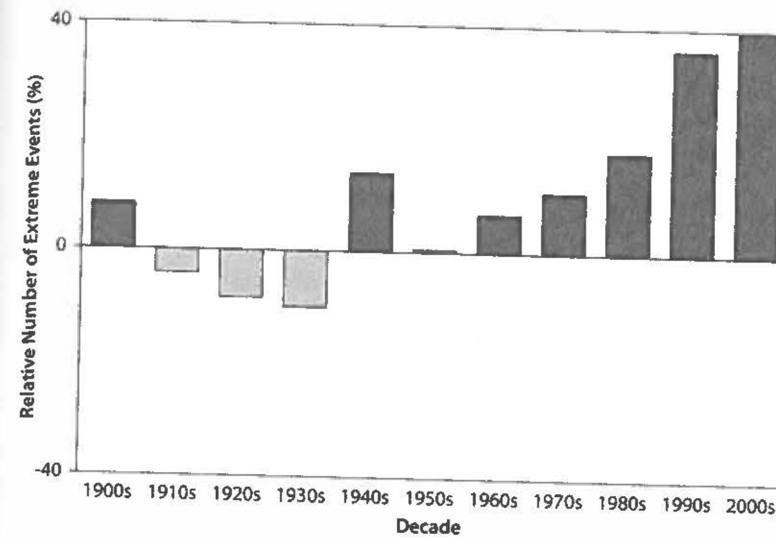


Figure 13. Heavy precipitation events in the United States since 1900. Illustration by Bill Nelson adapted from J. D. Walsh et al., "Our Changing Climate," in *Climate Change Impacts in the United States: The Third National Climate Assessment*, ed. Jerry M. Melillo, Terese Richmond, and Gary W. Yohe (Washington, D.C.: U.S. Global Change Research Program, 2014), 19–67.

an entire crop can be lost in a single devastating event. Imagine the damage done by hailstones measuring 22 centimeters in diameter, like the one in Argentina in 2018 that broke the world record! Severe storms are likely to intensify with continued climate disruption, and water (in both liquid and solid forms) will regularly pummel the land's surface, challenging the soil and its stewards.[40]

Climate change is typified by extremes of wet and dry, wind and heat. While some parts of the world are being bombarded with water, other parts are becoming parched, contributing to another form of land degradation—desertification. The world population experiencing desertification since 1961 has doubled, and the frequency of dust storms has increased sharply. The interaction of hotter temperatures, a more variable climate with less rainfall in some regions, and changing ways of using land—including urbanization—have driven a surge in desertification, which in turn promotes soil erosion. Droughts have increased in Amazonia, northeastern Brazil, the Mediterranean, Patagonia, most of Africa, and northeastern China.[41] As global warming marches ahead unchecked, soil erosion and degradation are bound to increase. People drive soil erosion indirectly by accelerating climate change. We drive it directly by how we treat the land.

As farmers continue to plow, as cities continue to sprawl, and climate change continues to intensify the very weather patterns that cause erosion, more topsoil will disappear. During the twentieth century, scientists debated whether soil was not, in fact, a renewable resource. We no longer have the luxury of continuing this debate in the face of soil loss rates that exceed agricultural rates by one hundredfold in some regions. In 2015, the International Year of Soils, the United Nations declared soil finite and predicted a catastrophic loss within sixty years.[42]

But why does extinction of topsoil constitute a crisis? And what are the effects along the way, when only some of the soil has been lost? To answer, we must explore the impacts of erosion around the planet.

6
Rocky Planet

Imagine standing on a planet with a rocky surface that emits no odor and is unable to sustain life. A gust of wind stirs sand particles into the air, obscuring a bright blue sky. When it rains, rivulets carry sand and gravel to gullies and then rivers, filling them with sediment. Silt, pebbles, and boulders have replaced the spongy, fragrant carpet that once gave the land its life force. This is a world without soil.

There will always be soil on Earth as long as there are forests and prairies to nurture it, but what if much of our sloped agricultural land lost its fertile topsoil and began to look as if it belonged on a rocky planet? The loss of food security would be enormous, the loss of beauty incalculable. We are not at the rocky planet stage now, but erosion is already affecting landscapes and food production world-