# *Ohio's Professional Soil Scientists*

## 2022 Spring-Summer Newsletter
## Volume 49, Issue 2-3 Part 2

### A World Without Soil – the past, present, and precarious future of the earth beneath our feet

by Jo Handelsman, published 2021 by Yale University Press

Book Review (by Kathy Sasowsky):

Written for the lay person, but informative for soil scientists, this new book hopes to prompt all to appreciate soil more. "Dirt" as she describes is derived from Old Norse with a root that means "excrement", and we all know that is *not* our profession. We will be familiar with many of the topics she discusses, but there is always more to learn about soil, as we all know.

This was a Christmas present, and I was so disheartened from the beginning of the book to read that battles that I thought had been won, were in fact, not won. The author is around my age, and had also learned about no-till agriculture, contour plowing, and strip contours – all efforts to stem soil erosion. The National Food Security Act and the terrific efforts of USDA NRCS to curb soil erosion had been very successful. The problem that I had not been aware of was "…after 1985, Congress weakened the language of the legislation repeatedly until the NRCS had little power to hold farmers accountable for soil protection." "On the eroded land, nutrient loss, yield reduction, land devaluation, and loss of biodiversity must all be accounted for in cost estimates. Off-site erosion costs range from sediment deposition, flooding, need for water treatment, increased food prices, and intensifying climate change." Even small losses in production can impact family farms. Let's "…preserve soil rather than squander it…."

Our country is more successful than most others at protecting soil; developing countries have raging problems with soil erosion and desertification. "Over the past seventy years, the United States has contributed 50 percent of total food aid…., "so the preservation of global soil affects us here. The impacts are in food security, climate change, water supply, disease, immigration, and global stability. "The United Nations reports that cumulative land degradation – 80 percent of it caused by soil erosion – is harming the welfare of 40 percent of the world's population, contributing to global and regional conflict, and causing mass migrations." "Local food shortages worsen as rivers fill with sand, preventing fishermen from catching small fish to use as bait for larger ones. In northern Nigeria, where the climate is characteristically hot and dry, crops grown in unhealthy or eroded soil are more susceptible to drought." We still have our work to do. And there is a link between soil erosion and climate change; the latter causes the former and the former exacerbates the latter.

Descriptions of soil structure formation and its benefits to soil health are described: "As plants develop a foothold, they slough off polysaccharides (long, stick strings of sugars), protein, and DNA that together form a thick mucus that binds soil particles into aggregates or clods and makes a wholesome broth for microbial residents." As we know, stronger structure means higher infiltration rates; higher infiltration means less runoff and less water erosion. Also we know that an increase in organic matter improves soil structure, also increases infiltration rates and soil health. Additionally, "Higher soil organic matter fosters higher biodiversity, which in turn reduces plant disease."

Another soil-related benefit is related to water quality. One third of American citizens rely on the soil to filter their water, sometimes with no other filtration. "…soil is excellent at filtering out pathogens, which is why manure is usually a safe fertilizer." "…most do not reach the groundwater." We think of microbes as being pathogens and yet in the soil, "…fewer than 1 percent of its bacterial species are readily culturable…."; this means that soil is the necessary medium for them. In turn, I would argue for our microbiome health, we need food grown in healthy soil. Humans have more microorganism cells in their bodies than human cells. "…the vast majority of life is microbial." "And nowhere is the diversity of microbes greater than in the soil." Pharmaceutical companies have abandoned soil (used from 1940's to 80's) as a source of new antibiotic treatments, in search of more lucrative maintenance drugs, despite evidence that soil could have a plethora of potential health uses, including fighting antibiotic resistant infections.

Fortunately, we know how to preserve soil, to increase its health, and to aid in solving many world problems. Somehow we need to keep getting the word out about soil! "…Bhutan's verdant forests, which are constitutionally mandated to cover at least 60 percent of the land.," based on a philosophy that they measure "…Gross Nation Happiness – rather than GDP to create and assess national policy." They also value their hydroelectric industry which requires a lack of sediment, and therefore a lack of soil erosion. In contrast is Indonesia, "…the world's fourth most populous country.", where "Sediment records indicate that erosion tracks closely with population density…." Indonesia is dominated by almost all small landholders, who "…are most vulnerable to the effects of soil erosion." This is not only true there, but globally, so global food supply, security, and soil preservation is critical. We know no-till and conservation tillage, cover crops, crop rotation help organic matter in soil, microbes, and soil health. Unfortunately, globally these are not practiced. We need to communicate globally about our known solutions, which pay off in the long run by preserving soil, increasing yield, decreasing water use, etc. More data is showing that well-managed livestock grazing, especially in semi-arid regions, can improve soil organic matter and water retention. Rather than prohibiting practices, can we encourage and compensate farmers for healthy soil practices which will benefit all of us in the long run?

On a related topic: "In 2019, all major greenhouse gases reached record high concentrations, including carbon dioxide, which reached 409.8 parts per million, the highest level on record in ice cores that encompass eight hundred thousand years." "As more land warms, …more extreme rainstorms deliver water more quickly…." "People in poorer countries are four times more likely to be displaced from their homes by extreme weather events than those in wealthy countries…." Because "Soil…[contains] the largest terrestrial store of carbon." It is a sink for carbon. Soil has "…more than the total amount released by human activities since 1750…." soil is critical for climate moderation. Gelisols "…sequester roughly one quarter of all organic carbon in soil." "Prairie plants that gave rise to Mollisols transport copious organic carbon into their roots, producing more biomass below ground than above." Switchgrass, which is a perennial that has great potential for a biofuel and is much better for soil health than corn, has roots that penetrate (as reported in this book) 3.5 m, as opposed to 0.2 m for corn, or 0.06 m for turfgrass!

Methane, a very potent greenhouse gas, is released from wetlands that have insufficient oxygen. Rice production can be increased by increased oxygen, addition of straw, and methanotrophs (microorganisms that eat methane as food). Draining wetlands can increase carbon dioxide. Nitrous oxide, an extreme greenhouse gas can be emitted from nitrogen fertilizer. Moderate oxygen levels moderate nitrous oxide emissions. There are known scientific practices that can help agriculture improve its contributions to climate change without sacrificing yield. As much as agriculture is blamed for greenhouse gases, "The majority of anthropogenic [people-derived] sources of greenhouse gases are the result of burning fossil fuels…." Emphasizing soil health can benefit the farmer, the society, and the environment.

The author, Jo Handelsman, is a professor at the University of Wisconsin-Madison and former science advisor to President Obama.

## A Memory from Tim Gerber


This is the text in the 1992 Threshold Acre Celebration brochure. A scan of the brochure cover is in file identified as "Threshold scan.jpg."

A Cause for Celebration

After 93 years of field work by hundreds of professional soil scientists, a detailed inventory of the soils of Ohio has been completed. The Association of Ohio Pedologists is planning the Threshold Acre Celebration to commemorate this important scientific achievement.

The last acre of soil in the state to be mapped is considered to be a "threshold," because much remains to be done. Because of different uses for soils and an increase in the knowledge about soils, soil surveys need to be updated or "modernized" periodically.

Some of Ohio's citizens who are faced with land use decisions will require even more detailed information from a soil scientist at specific sites. Others will need training on how to use the published information. The information itself will need to be adapted to new formats to facilitate its use.

The dedication ceremony will be held during the 1992 Farm Science Review. More than 150 soil scientists – most of whom are retired from public service – are also being invited to a reunion to be held at the Madison County Fairgrounds in London on the evening of September 21.

The Ohio Soil Survey

The first soil survey of Ohio was conducted in Montgomery County in 1899 by the U.S. Department of Agriculture (USDA). The report identified seven different kinds of soils in the county. In 1915, the ***Reconnoissance Soil Survey of Ohio*** was published, and it identified 26 basic kinds of soils in the state.

Between 1900 and 1939, soil surveys for 32 counties and 5 urban areas were published by the USDA. The Ohio Soil Survey was led during the 1920s and 1930s by Dr. Guy W. Conrey of The Ohio State University, Department of Agronomy and the Ohio Agricultural Experiment Station (OAES).

Only four more soil surveys were completed by 1951, but improvements were evident in each of the publications. The map scales nearly quadrupled, and the ***Soil Survey of Fairfield County*** was the first one to have soil maps published on aerial photographs.

In 1952, a new agency was created – the Division of Lands and Soil – within the Ohio Department of Natural Resources (ODNR). The division was organized "to complete as rapidly as possible, an accurate and workable soil and land use inventory of the state." In the same year, the Soil Conservation Service (SCS) became the USDA agency responsible for directing the national soil survey program.

Direction for the revitalized Ohio Soil Survey came from the Soil Inventory Board. Field soil scientists of ODNR and SCS completed soil surveys in four more counties in the 50's and 21 more in the 60's.

Meanwhile, researchers at OSU studied the soils in these inventoried counties to better understand the differences between Ohio's soils. An OAES laboratory analyzed critical properties of soil samples collected by the field soil scientists.

Some of the older, less detailed soil surveys were replaced in counties where the need for more information on soils and their uses was recognized. By 1982, the state had 64 "modern" soil surveys. That year the Huron County Commissioners signed a contract to share in the cost of modernizing the oldest of them. Since then, soil survey modernization projects have begun in 11 other counties.

Since 1974, when ODNR developed the Ohio Capability Analysis Program (OCAP), soil survey information from 54 counties has been digitized for computer analysis. Plans call for information from all future soil survey modernization projects to be digitized by the Division of Soil and Water Conservation's OCAP staff for use in a variety of geographic information systems.

Cooperating Agencies

The following agencies have made the progression of Ohio's soil survey possible, and participate as members of the Soil Inventory Board: USDA Soil Conservation Service.
ODNR Division of Soil & Water Conservation, Ohio Agricultural Research & Development Center, OSU Department of Agronomy, and Ohio Cooperative Extension Service.

The Soil Inventory Board responds to the expressed interest of local officials regarding soil survey projects. Locally, the Soil & Water Conservation Districts (SWCD) commonly take the lead in bringing together the parties that are most interested in having up-to-date soil survey information.

The team of soil scientists who have accomplished this important task are indebted to SWCD staff members and other local officials who have provided their assistance. During the past 20 years, local sources have also contributed as much as 25 percent of the cost of soil survey projects.

Sponsorship

The **Association of Ohio Pedologists**, organized in 1976 and dedicated to maintaining professionalism among soil scientists, is hosting this event. It is affiliated with the American Registry of Certified Professionals in Agronomy, Crops and Soils (ARCPACS). Membership includes publicly and privately employed soil scientists and consultants.

## The Technical Corner

This is a new column open to any and all members who want to discuss technical issues, equipment, new methodologies, observations, any of the discussions that we would typically have at field days and training sessions which, because of the Covid-19 Pandemic, have not been available to us at this point in time.  The Executive Committee is hoping that this column will encourage the ongoing dialogue that has made AOP gatherings so very informative.  We may also find that these materials can be used for training the next generation of soil scientists.  Would you like to be next?

## They are Here!  They are Wonderful!

I'm including Mike's write up from last newsletter as it explains how the interactive maps were made. I'll then include pictures, links and a short history to sum up this incredible effort, 200 years in the making.

## New Exciting Maps from ODNR DGS – Mike Angle

### Ohio Geological Survey to release new series of Groundwater Vulnerability Maps

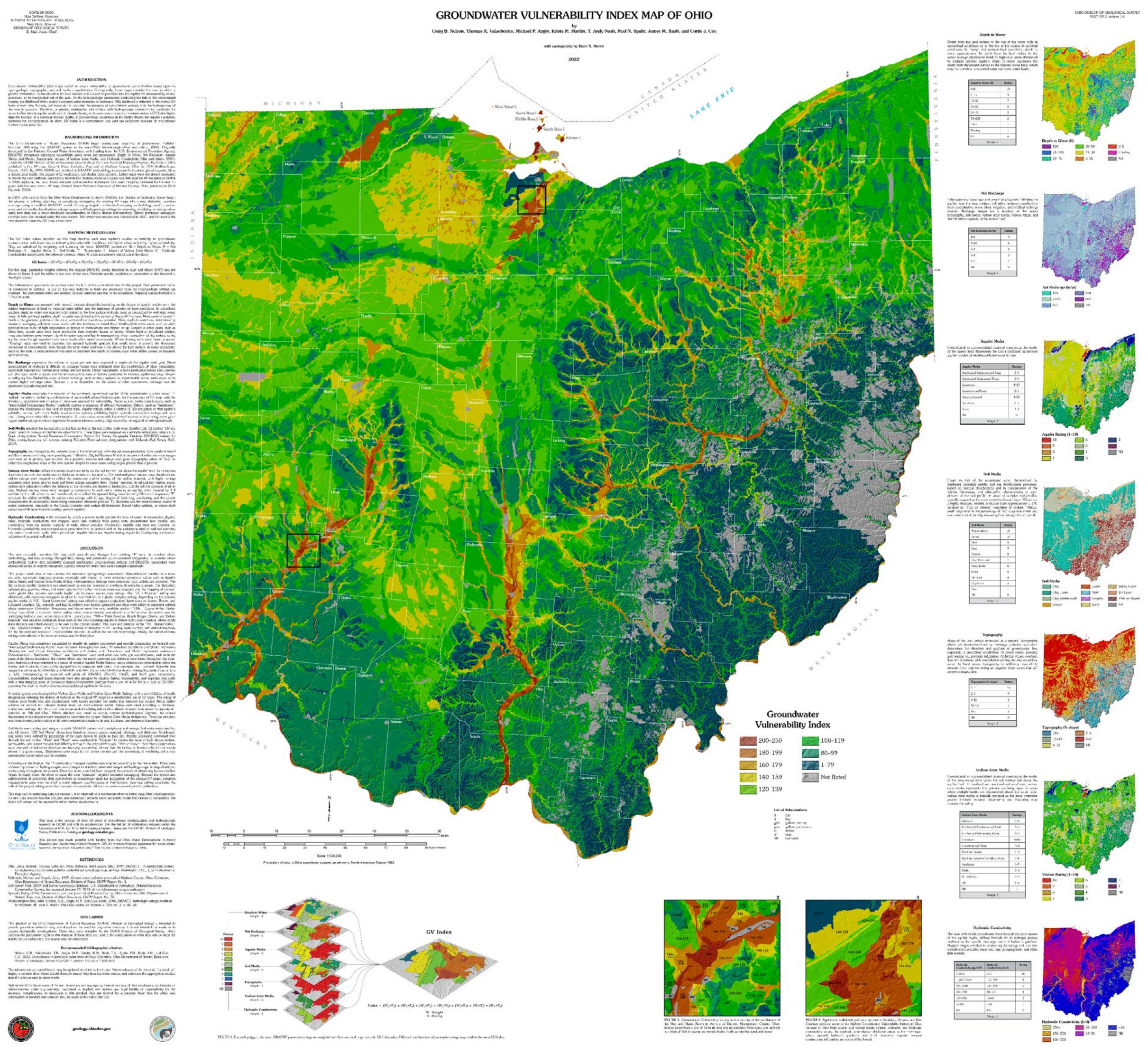
By Mid-January, the ODNR, Division of Geological Survey, Groundwater Group will be releasing a new seamless series of statewide Groundwater Vulnerability (GV) Maps. This effort is a culmination of a three year project, partially funded by a grant from the Ohio Water Development Authority (OWDA) The GV maps are compiled using the DRASTIC system and will replace the earlier series of Groundwater Pollution Potential (GWPP) Maps that have been in existence since the late 1980's. DRASTIC is an acronym for the seven components that are evaluated:  **D**epth to water, net **R**echarge, **A**quifer media, **S**oil Media, **T**opography (% slope), **I**mpact of the vadose zone media, and hydraulic **C**onductivity. These components are evaluated and a vulnerability index (aka DRASTIC number) is derived. Every polygon is assigned the vulnerability index number along with a hydrogeologic setting. The hydrogeologic setting quickly infers the geologic setting (often landscape, aquifer and/or vadose zone). Examples include Buried Valleys, Thin till over Sandstone, Glacial Lakes, etc.

The new seamless GV maps will have improvements over the earlier GWPP series. The settings and ratings have been standardized and revaluated and earlier border matching issues have been resolved. The GWPP series was mapped over 30+ years and a variety of authors, methods, and mapping philosophy changes were made. Technologically, roughly the first 45 counties were mapped using paper and mylar methods with a slow conversion to GIS beginning about 2000. The first maps totally created in GIS occurred about 2007. All the previous existing maps were revaluated, checked, and matched in order to create the seamless GIS coverage. In addition, 11 new counties, mainly along the Ohio River in SE Ohio were mapped for the first time.

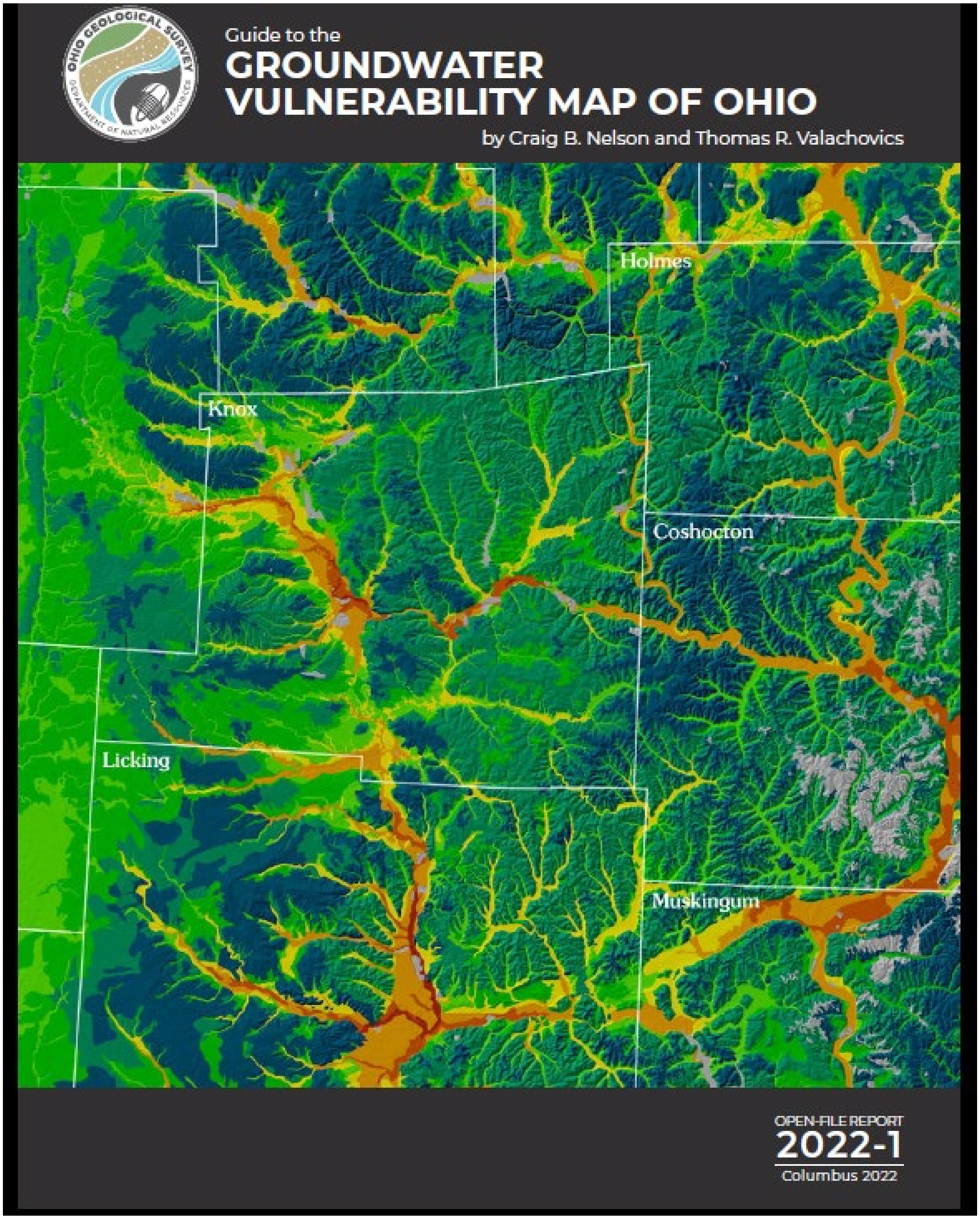
Soil scientists will be most interested in the soil media, slope, impact of the vadose zone media, and the net recharge components.  Soil media are derived from looking at the overall soil profile and determining how restrictive to water flow the soil profile is. Soil types with ratings in ascending order are clay (1), clay loam (3), silt loam (4), loam (5), sandy loam (6) high shrink-swell clay (7), peat/muck (8), sand (9), and gravel (10) and thin or absent (10). Thin or absent soils contain bedrock in their profiles, usually within 54 inches. Slope was derived from looking at DEM and hill shade in GIS and follows increments used in soil mapping: 0-2%=10, 2-6%=9, 6-12%=5, 12-18%=3, and >18%=1. The vadose zone is typically the soil parent material and includes till, alluvium, outwash, and various bedrock lithologies. The vadose media ratings will vary depending upon texture, lithology, compaction, fracturing, weathering, etc. Recharge ratings are somewhat of a summation of all the other properties and are rated in increments of inches per year such as 2-4 in/yr, 4-7 in/yr, etc.

The hydrogeologic setting, vulnerability index number, and all of the component ratings can be viewed by polygon in GIS. There will be an interactive map on the Geological Survey's website by mid-January. In addition, both the Hydrogeologic Setting and Vulnerability Index will be in layouts for wall maps.

The hard copy link, https://ohiodnr.gov/static/documents/geology/GW2_Nelson_2022.pdf.
The interactive link: https://ohiodnr.gov/discover-and-learn/safety-conservation/about-odnr/geologic-survey/groundwater-resources/groundwater-vulnerability-map
The Explanation Document: https://ohiodnr.gov/wps/wcm/connect/gov/e3fe9649-96b9-427d-baf2-c6b92b8d4fd7/OFR2022_1_Nelson_2022_web.pdf?MOD=AJPERES&CONVERT_TO=url&




This interactive map is the columniation of the efforts of hundreds of scientists, engineers, surveyors, drillers and miners who have worked in Ohio for over 200 years. The efforts began on foot and on horseback with survey chains, stadia rods and later levels, plane tables and alidades and ended up using remote sensing, satellites, aerial overflights and geographic information systems (GIS). When the work began, no one had begun to use airplanes, automobiles, let alone dreamed of computers, but all the work and all the layers in this interactive map came from all those pieces. As Tim Gerber pointed out above, the soils layer alone took almost 100 years. The surface elevation layer goes back to the beginning surveys in Ohio, including the canal building efforts where surveyors on horseback found the flattest routes across the state to build the canals which took Ohio produce to markets to the east.


OHIO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
Guide to the
GROUNDWATER VULNERABILITY MAP OF OHIO
by Craig B. Nelson and Thomas R. Valachovics
Holmes
Knox
Coshocton
Licking
Muskingum
OPEN-FILE REPORT
2022-1
Columbus 2022

How many water wells have been dug and drilled in Ohio to be used to determine the depth to water? Certainly more than a million in the last 250 years. Schoenbrunn Village at New Philadelphia is 250 years old this year, the oldest white settlement in Ohio. We know the Native Americans in the region were mining drift coal from local stream cuts in the area even before the Moravian settlements were founded. So the records that document the bedrock, the aquifers may go back that far, as well. In this interactive map, we have the whole earth sciences records summarized in one place, helping us to understand, at the flick of a computer button, how easy or how difficult it would be to contaminate the ground water at any one spot by installing a potentially contaminating land use at that location. As you go forward, locating potential septic systems sites, I hope you refer to this interactive map often and that you give a bit of thanks to all of those folks that went before us to make our work even possible.

## Journal Articles etc. of note

**From Duane Wood**

### Farm vehicles are now heavier than most dinosaurs: Why that's a problem

May 18, 2022

What does a modern combine harvester and a Diplodocus have in common? One answer, it seems, may be their big footprints on the soil. A new study led by researchers from Sweden and Switzerland has found that the weight of farming machinery today is approaching that of the largest animals to have ever roamed the Earth—the sauropods.

Depicted as the giant, friendly “veggiesaurus” in the movie “Jurassic Park,” sauropods were the biggest of the dinosaurs. The heaviest were thought to weigh in at around 60 metric tons—similar to the weight of a fully laden combine harvester. Tractors and other machinery used on farms have grown enormously heavier over the past 60 years as intensive, large-scale agriculture has become widespread. A combine harvester is almost ten times heavier today than it was in the 1960s.

The weight of animals or machines matters because soils can only withstand so much pressure before they become chronically compacted. They may not look it, but soils are ecosystems containing fragile structures—pores and pathways which allow air to circulate and water to reach plant roots and other organisms. Tires, animal hooves and human feet all apply pressure, squashing the pores, not just at the surface but deeper down too.

Soil compaction can cut plant growth and harvests, and increase the risk of floods as water runs off the land and reaches waterways more quickly. The scientists involved in the new study took a look at how much compaction is being caused by these giant farming machines and compared it with the sauropods who lived over 66 million years ago. They found both to be big culprits of compaction.

**Under pressure**

The study points out that as the weight of farm machinery has grown, tire sizes have ballooned too, adjusting the area of contact between the vehicle with the soil to reduce the pressure on the surface and help avoid sinking. It seems that animals evolved with a similar strategy—increasing foot size with weight to help avoid sinking into the soil.

Overall, pressure at the soil surface has remained fairly constant as farm machinery has gained weight. But the authors suggest that stresses on the soil continue to increase below the surface and penetrate deeper as vehicles (or animals) get heavier. Farm machinery today (and the sauropods of the past) are now so heavy that they irreparably compact soil below the first 20 cm, where it isn’t tilled. Aside from restricting how deep the roots of crops can grow to seek water and nutrients further down in the soil, this can also create low-oxygen conditions that are not good for plants or the organisms they share the soil with.

**Where did the dinosaurs go for dinner?**

This creates a "sauropod paradox," as the researchers call it. The dinosaurs and the loads transmitted through their feet were so large that they would have likely caused significant subsurface damage to soils wherever they roamed, potentially destroying the soil's ability to support the plants and ecosystems they would have relied on as their food source.

The image of sauropods roaming widely and foraging freely as depicted by Jurassic Park seems unlikely, as they would have had an unsustainable influence on their environment. So how did they survive?

The scientists behind the study speculate that they may have kept to well-trodden paths, limiting their impact while browsing the canopy with their long necks. How exactly a sauropod could live in equilibrium with the soil remains a mystery for now.

**Big food for thought**

A more pressing conundrum is how to reconcile soil compaction by farming vehicles with sustainable food production today. The risk of soil compaction varies with the type of machinery and the way it's used, as well as the type of soil and the moisture bound up in it.

The study estimates that 20% of croplands globally are at high risk of losing productivity because of subsoil compaction by modern agricultural vehicles, with the highest risks in Europe and North America where it's relatively moist and there are more large farms using the largest machines. Clearly, this is an issue in arable landscapes, but the problem also extends to grasslands where silage is baled, and urban landscapes where the movement of construction vehicles on green space is not well controlled.

The authors call for design changes to machinery to help maintain the soil's structure. We suggest another option. To reduce their impact on the soil, we could reduce the need for such large machines in the first place by growing food using smaller machines on smaller parcels of land, particularly in high-risk zones. Finding ways to break up vast monoculture landscapes makes sense for many other reasons. For example, wildflower field margins, hedgerows and trees can help sequester carbon, manage water quality and support biodiversity.

Soil can only withstand so much pressure—whether from compaction or other threats such as continual harvesting, erosion or pollution. Humans must act to reduce pressures on soils, or we risk going the way of the dinosaurs.

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Risk of soil degradation and desertification in Europe's Mediterranean may be more serious than realized

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**More information:**

Thomas Keller et al, Farm vehicles approaching weights of sauropods exceed safe mechanical limits for soil functioning, *Proceedings of the National Academy of Sciences* (2022). DOI: 10.1073/pnas.2117699119

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Farm vehicles are now heavier than most dinosaurs: Why that's a problem (2022, May 17)

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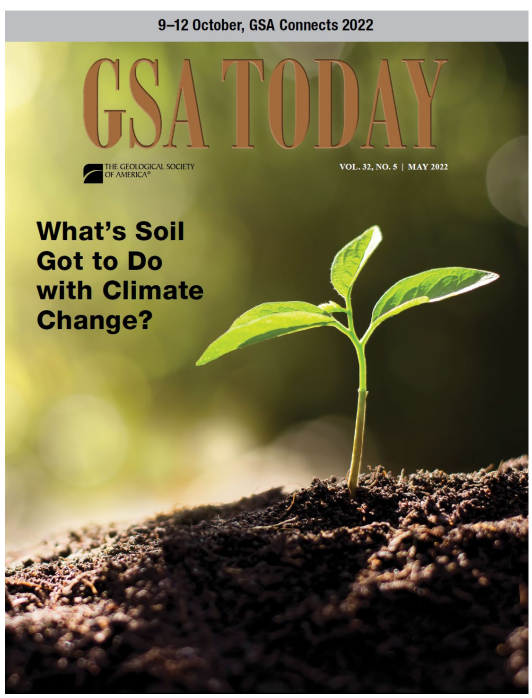
from https://phys.org/news/2022-05-farm-vehicles-heavier-dinosaurs-problem.html

**From Kathy Sasowsky**



THE GEOLOGICAL SOCIETY OF AMERICA®

# What's Soil Got to Do with Climate Change?

***Todd Longbottom, Leila Wahab,*** *Dept. of Life and Environmental Sciences, University of California Merced, Merced, California 95343, USA;* ***Kyungjin Min,*** *Dept. of Life and Environmental Sciences, University of California Merced, Merced, California 95343, USA, and Center for Anthropocene Studies, Korea Advanced Institute of Science and Technology, Daejeon, South Korea;* ***Anna Jurusik,*** *Dept. of Life and Environmental Sciences, University of California Merced, Merced, California 95343, USA;* ***Kimber Moreland,*** *Atmospheric, Earth, and Energy Division, Lawrence Livermore National Laboratory, Livermore, California 94550, USA;* ***Manisha Dolui, Touyee Thao, Melinda Gonzales, Yulissa Perez Rojas, Jennifer Alvarez, Zachary Malone, Jing Yan, Teamrat A. Ghezzehei,*** *and* ***Asmeret Asefaw Berhe,*** *Dept. of Life and Environmental Sciences, University of California Merced, Merced, California 95343 USA*

## ABSTRACT

Soils are the foundation of life on land and represent one of the largest global carbon (C) reservoirs. Because of the vast amount of C that they store and the continuous fluxes of C with the atmosphere, soil can either be part of the solution or problem with respect to climate change. Using a bank account analogy, the size and significance of the soil organic C (SOC) pool is best understood as the balance between inputs (deposits) from net primary productivity and outputs (withdrawals) from SOC through decay and/or physical transport. Reversing the current problematic trend of increasing concentration of greenhouse gases in the atmosphere must be met with reduced fossil fuel emissions. At the same time, we argue that "climate-smart" land management can promote both terrestrial sequestration of atmospheric carbon dioxide ($CO_2$) and contribute to improving soil health and benefits. In this review, we highlight environments that are particularly vulnerable to SOC destabilization via land use and climatic factors and outline existing and emerging strategies that use soils to address anthropogenic climate change.

## INTRODUCTION

The health and diversity of natural ecosystems—and human civilization—depend on our coordinated responses to global changes that threaten earth's long-term habitability. Soils, the thin veneer on the global land surface that supports terrestrial life, are an integral component of anthropogenic climate change mitigation strategies (Paustian et al., 2016; Loisel et al., 2019). Soils are a necessary part of the solution for human-induced climate change because they represent one of the largest terrestrial carbon (C) reservoirs, storing twice as much C as the earth's atmosphere and vegetation combined (up to 2500 Pg C; IPCC, 2013; Friedlingstein et al., 2020). Terrestrial C pools are a powerful C sink, with the potential to offset up to 30% of anthropogenic C emissions, where some of the sequestered C persists in soil over millennial time scales (Friedlingstein et al., 2020). Because of the relative sizes of the different C reservoirs, even slight changes in the amount of C stored in soil can represent significant changes in the global atmospheric concentration of carbon dioxide ($CO_2$) and the earth's climate future.

How do we unlock soil's potential for combating climate change? An important component of a comprehensive response is to store more C in soils, particularly in soil pools that cycle C at slower rates compared to the other reservoirs (ex., atmosphere, biomass, and on near surface soil layers) (Schmidt et al., 2011). The amount of carbon stored in soil (soil organic C or SOC) is a balance between inputs and outputs of carbon (Berhe, 2019a; Lavallee and Cotrufo, 2020). SOC storage in a given area (plot, catchment, region, or another spatially constrained system) has been likened to a bank account, where the "balance" is the bulk SOC stock or inventory (Fig. 1). Bank "deposits" are contributed by vegetation litter, root exudates, living soil biota, deposition of eroded C, and remains of formerly living organisms. The depletion of the balance in the soil carbon bank account is driven by microbial decomposition of organic C inputs to $CO_2$ and dissolved and particulate transport of C through leaching and/or erosion.

The SOC that exists in soil can be subdivided into "slow-cycling" and "fast-cycling" pools akin to checking and savings accounts (Lavallee and Cotrufo, 2020), respectively. Slow-cycling C is either mineral-associated C that is found physically protected in soil aggregates or chemically bound to the surfaces of reactive soil minerals; both mechanisms restrict decomposition and associated losses of SOC, allowing it to persist in soil for decadal to millennial time scales (Schmidt et al., 2011; Hemingway et al., 2019). In contrast, fast-cycling C is more readily degradable and prone to physical transport in shorter time scales (Schmidt et al., 2011; Hemingway et al., 2019). Fast C cycling, which is akin to funds in a checking account, is critical for maintenance of life in soil, because decomposition is the main mechanism that recycles nutrients needed by organisms that call the soil home (Janzen, 2006). Even small, but sustained, deposits into the soil C savings account over time allow for long-term buildup of C in the slow-cycling pool with significant potential for climate change mitigation.

Increasing urgency for addressing the global climate emergency demands that we reduce the release of greenhouse gasses from burning of fossil fuels, while finding appropriate alternatives to draw down some atmospheric carbon through soil carbon sequestration and other means. As we seek these solutions, it is important to remember that decomposition of organic matter (i.e.,

*GSA Today*, v. 32, https://doi.org/10.1130/GSATG519A.1. CC-BY-NC.

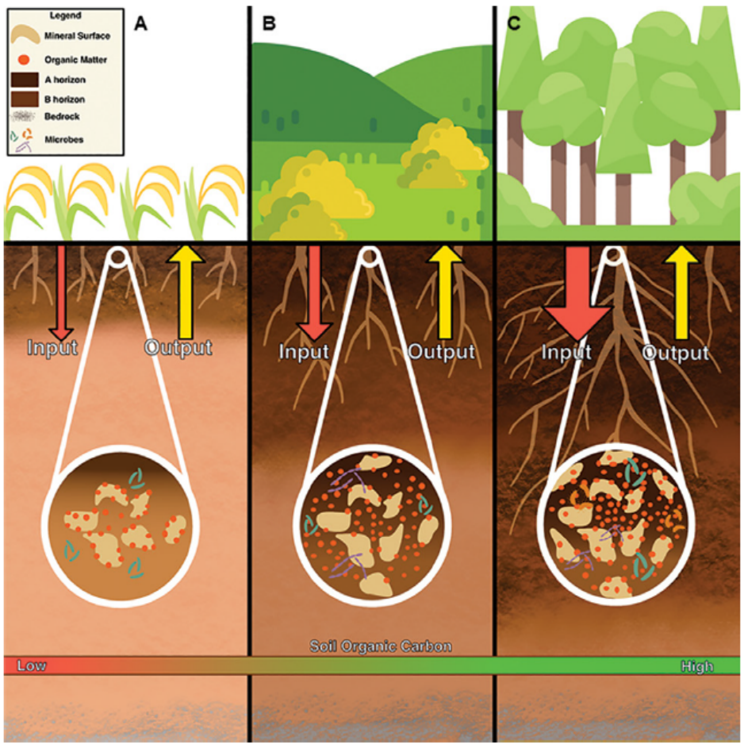



**Figure 1. Soil organic carbon (SOC) is a dynamic and complex admixture. Here, three contrasting ecosystems reveal differing SOC richness and dynamics: (A) agricultural, (B) grassland/shrubland, and (C) forested. Conventional agriculture (A) often leads to lower carbon stocks, and overall, less carbon input to the soil carbon pool. Grasslands (B) can harbor plants with deeper and more extensive root systems, medium to high amounts of SOC stock, and greater carbon inputs to the SOC pool. Forests (C) can have the deepest rooting system, a high amount of soil C stock, greatest density of mineral-associated C, and high rate of input of C to soils. Overall, organo-mineral association(s) and SOC pool is a function of the "balance" of C inputs and outputs in the soil organic carbon "bank account."**

withdrawal of some of the balance from the soil carbon checking account) is a critical ecosystem process because decay of organic residue provides essential nutrients for plants and microbes in soil (Janzen, 2006). For this reason, we cannot expect zero withdrawals from the soil carbon bank and must figure out how we can continue to "invest" in soil C to maximize its input and retention in the soil, thus preventing fast release of C as greenhouse gasses to the atmosphere. Maintenance of soil health through "smart" management practices has been proven to simultaneously achieve SOC sequestration and provision of clean air, water, and a functional habitat (Billings et al., 2021; Kopittke et al., 2022). Here, we explore prevailing issues with conventional soil management, vulnerability of SOC to loss in a changing world, and strategies to alleviate climate-change impacts on soil resources. In this framework, we identify strategies for soil C sequestration and ways to prevent "overspending" in an uncertain future marked by changing climate and increased demands to ensure food and nutritional security of the growing human population.

## CARBON LOSSES DUE TO CONVENTIONAL SOIL USE AND DEGRADATION

An increasing human population and onset of the industrial age led to an increased demand for food, energy, and water resources, and overall intensification of the agricultural sector. With intensive agricultural practices came large-scale degradation of the global soil resource that included increased rates of soil erosion (i.e., loss from working lands) that outpaced new soil production by 1–2 order(s) of magnitude, largely resulting from deforestation to clear land for agriculture, conventional tillage practices, and overgrazing (Lal, 2004; Montgomery, 2007). Conventional land management practices cause physical disturbance of soils and have historically promoted enhanced agricultural yields, to the detriment of SOC content, topsoil thickness, and overall soil health and structural stability (Phillips et al., 1980; Reganold et al., 1987; Amundson et al., 2015). The systematic exploitation and modification of undisturbed soils has led to the resulting agricultural soils being dubbed "domesticated," lacking hallmark resilience of their wild predecessors (Amundson et al., 2015). Soil domestication for agriculture also presents broader, associated ecosystem issues, such as diminished biodiversity from engineered crop community monocultures, introduction of chemical pesticides to hydro- and pedospheres, and the delivery of vast quantities of esp. nitrogen and phosphorus fertilizers to coastal margins. Conservation tillage and organic farming have been proposed as alternative approaches that enhance soil health and to limit unsustainable soil "mining" and associated SOC overspending (Montgomery, 2007). Estimates maintain that tillage management, when paired with cropping systems, can sequester 0.03–0.11 Pg C $yr^{-1}$ (Follett, 2001). Despite these promising advances, human civilization and associated changes in land use and land cover led to the loss of 120 Pg C in the upper ~2 m of soils since humans adopted agriculture, with the fastest rate of loss occurring in the past 200 years (Sanderman et al., 2018).

Land Use/Land-Use Change (LULUC) practices such as conventional agriculture, deforestation, and wetland conversion contribute 10%–14% of overall anthropogenic greenhouse gas emissions (Paustian et al., 2016). The SOC pools impacted by LULUC have the potential to release massive amounts of C to the atmosphere, making the preservation of these environments critical to protect soil C from loss both by reducing future releases of C from soil to the atmosphere (avoided fluxes) and promoting drawdown of C that is already in the atmosphere (sequestration of atmospheric $CO_2$). Deforestation was historically practiced to clear land for agriculture, but also continues to occur due to urban development, logging, and an increase in wildfire frequency and intensity. These activities can destabilize SOC, releasing slow-cycling C stored even in deeper soil layers (Drake et al., 2019). This also lowers ecosystem functions that SOC can provide, such as water retention and nutrient cycling (Veldkamp et al., 2020). Similarly, histosols (wetland soils, including peatlands with no underlying permafrost) can play a critical role because they make up only 1% of soils globally, yet contain a larger proportion of SOC (179 Pg C, or ~12% of SOC in the upper 100 cm globally: Brady and Weil, 2017). This SOC accumulation can be attributed to a lower rate of decomposition of SOC due to waterlogging and resultant limitation in availability of free oxygen for the heterotrophic soil microorganisms that can otherwise effectively decompose organic matter. Histosols have historically been targets for drainage and conversion to high-yielding agricultural lands (Holden et al., 2004). Draining of histosols, due to atmospheric warming and/or anthropogenic practices, can lead to rapid decomposition of SOC release to the atmosphere (Couwenberg et al., 2011). Overall, the soil system stores large amounts of carbon, but it has continued to experience rapid degradation due to human actions. However, adoption of climate-smart land management practices has a clear potential to reduce the atmospheric $CO_2$ burden and increase the amount of carbon stored in the soil carbon bank, with multiple benefits for improving ecosystem health and human welfare.

## VULNERABILITY OF SOC TO LOSS WITH UNCERTAIN FUTURE

Climate is a primary factor driving the rate of decomposition of SOC (Brady and Weil, 2017). Global climate change can accelerate SOC losses due to increasing global atmospheric temperature, altered precipitation patterns, and other changes (Bellamy et al., 2005; Walker et al., 2018). Warming often increases the rate of microbial decomposition of SOC and subsequent $CO_2$ efflux to the atmosphere (Lloyd and Taylor, 1994; Lehmeier et al., 2013; Min et al., 2019). The effects of increasing temperature on SOC losses vary with molecular complexity of SOC and environmental conditions (e.g., water limitation, aggregation, mineral association) (Davidson and Janssens, 2006). Complex SOC, with high activation energy, is more sensitive to temperature than simple SOC (Lehmeier et al., 2013; Lefèvre et al., 2014). The temperature sensitivity of protected, slow-cycling C has been less studied (Karhu et al., 2019), which necessitates future studies that explore the relationship between slow-cycling C and its sensitivity to environmental changes. Contrary to the positive relationship between temperature and SOC decomposition rate, increases in water availability can increase (Kaiser et al., 2015; Min et al., 2020) or decrease SOC decomposition (Freeman et al., 2001), depending on the systems of interest. Precipitation can also indirectly affect SOC storage by inducing soil erosion, changes in pore connectivity, and altering ecosystem structure (Pimentel et al., 1995; Smith et al., 2017; Wu et al., 2018). In eroding landscapes, lateral distribution of topsoil C and its deposition in lower-lying landform positions (Berhe et al., 2018) causes mixing of the relatively fast-cycling C with slow-cycling C in deep soil layers.

The response of carbon stored in soil to climate change and other perturbations varies depending on the nature of the soils and the type of change to the system (Berhe, 2019b). Here, we highlight how SOC will respond to climate change using three important areas of concern and uncertainty (e.g., gelisols, paleosols, and deep soil).

### Gelisols

Gelisols are soils of very cold climate conditions and store ~1000 Pg C in the upper 3 m of active and underlying layers of permafrost soils (Tarnocai et al., 2009; Hugelius et al., 2014). Gelisols have accumulated C because of climate-driven slow decomposition rates (Ping et al., 2015; Turetsky et al., 2020). Warming in the northern hemisphere is predicted to release 12.2–112.6 Pg C by 2100, according to Representative Concentration Pathway 4.5 and 8.5 warming scenarios (IPCC, 2013). This huge uncertainty in the projected C release in the northern hemisphere is partly due to considerable variability in hydrology, soil conditions, and vegetation (McGuire et al., 2009; Schuur and Abbott, 2011; Ping et al., 2015). The rapid destabilization of polar and high-altitude environments, often referred to as the most sensitive barometers of climate change, serves as a benchmark for understanding anthropogenic modifications to the global climate system.

### Paleosols

Paleosols are soils that developed in different environmental conditions when topsoil was transported downhill and buried by alluvial, colluvial, aeolian deposition, volcanic eruption, or human activities over centuries to millennia (Marin-Spiotta et al., 2014; Chaopricha and Marin-Spiotta, 2014). This process promotes SOC-mineral association(s) (Rumpel and Kögel-Knabner, 2011) that build up soil C stock in the slow-cycling soil C savings account (Schmidt et al., 2011). Recent estimates suggest that paleosol C is a significant global C reservoir (Lehmkuhl et al., 2016), but it is spatially variable depending on landscape and climate history, thus making it difficult to estimate the total storage. The effect of any environmental change on buried SOC is complex and poorly understood because paleosols are not considered for the global C stock inventory and models. The possibility of the vast storage of SOC raises questions on how the previously buried SOC will interact in the presence of water, modern soil surface microbes, and addition of new fresh SOC, and finally if they will become a sink or a source of greenhouse gasses in the presence of all the optimal conditions for decomposition.

### Deep Soil

The overwhelming majority of soil C studies have focused on shallow soil depths, with little attention paid to the amount of C stored in or the vulnerability of C in deep soil layers. Soils can develop to >10 m depth, and deep soils (below 30 cm) can store up to 74% of the total profile C with radiocarbon ages of 5,000–20,000 years old (Moreland et al., 2021). It is estimated that 28 Pg C is stored in soils with deep weathered bedrock, suggesting that deep soil C is a large C reservoir that may be potentially vulnerable to a changing climate (Moreland et al., 2021). Some soils are already showing evidence of warming by 2 °C, since 1961, which has been observed at up to 3 m depths (Zhang et al., 2016). Although decomposition rates are slower in deeper soils than in surface soils, recent studies have shown that deep SOC is more vulnerable to loss than previously thought (Rumpel and Kögel-Knabner, 2011; Hicks Pries et al., 2017; Min et al., 2020). Experimental warming to a depth of 1 m found that warming increased annual soil respiration by ~35% and estimated that with a 4 °C increase, deep soils have the potential to release 3.1 Pg C $yr^{-1}$, equivalent to 30% of fossil fuel emissions (Hicks Pries et al., 2017; Friedlingstein et al., 2020).

In the following section, we focus on "working lands," where the global soil degradation problem can be effectively addressed (in a cost- and time-efficient manner) through a suite of natural climate change solutions.

## SOILS AS NATURAL CLIMATE CHANGE SOLUTIONS

Intergovernmental Panel on Climate Change (IPCC) assessment reports and the Paris Agreement have highlighted the importance of immediate action to prevent catastrophic changes to the earth system. Inclusion of soils in local to global climate change mitigation strategies is a proven and cost-effective strategy. Natural climate solutions can provide 37% of cost-effective $CO_2$ mitigation necessary for a >66% chance of holding warming below 2 °C by 2030 (Griscom et al., 2017). The "4 per 1000" effort has proposed soil as a natural climate change solution and endeavors to increase SOC storage by 0.4% annually (Rumpel et al., 2020), thereby offsetting one third of global fossil fuel emissions. Here, we provide a review of the available solutions to increase the amount of C stored in the soil C savings account through a variety of land stewardship practices, including use of amendments such as compost, biochar, waste, and management interventions such as reforestation, inclusion of deep root perennials, and cover crops.

Restoring degraded lands and avoiding further land conversion (e.g., afforestation) can also help mitigate climate change (Fig. 2; Table 1). Afforestation of degraded sites in the United States is estimated to potentially sequester 2.43 Pg C $yr^{-1}$ in the upper 30 cm of soil over 30 years (Cook-Patton et al., 2020). Although afforestation efforts can increase SOC storage on decadal time scales, the effects are largely site-specific. For example, depending on the prevailing climate of an area, restoring grasslands might be a better option for C sequestration

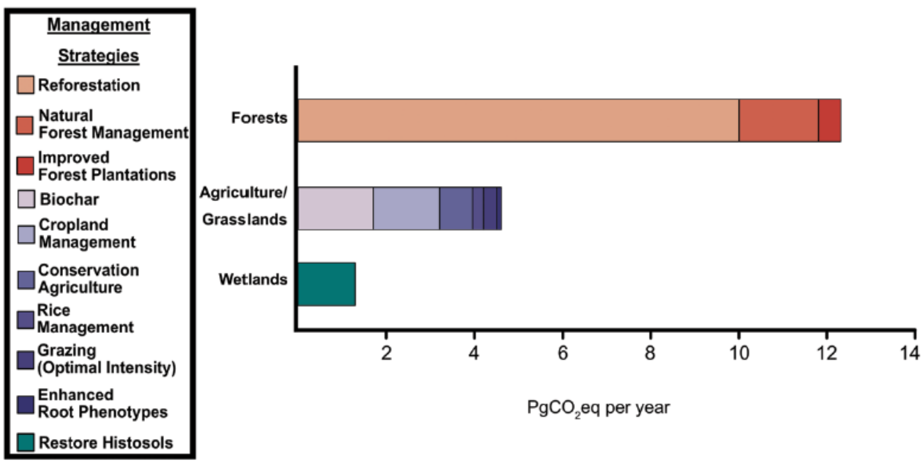



**Figure 2. Various management strategies in forested, agriculture/grassland, and wetland ecosystems exhibit differing propensities to take up $CO_2$. Overall, these strategies represent a way to expand terrestrial ecosystem uptake of carbon (Friedlingstein et al., 2020; Paustian et al., 2016; Griscom et al., 2017).**

TABLE 1. CLIMATE MITIGATION POTENTIALS OF VARIOUS LAND USE PRACTICES ACCORDING TO POSSIBLE AREA OF PRACTICE ADOPTION

| Practice | Climate Mitigation Potential (Pg $CO_2$ eq $yr^{-1}$) | Area of Practice Adoption (Mha) | References |
|---|---|---|---|
| **Forests** | | | |
| Reforestation | 10 | 3665 | |
| Natural forest management | 1.8 | 3665 | 1, 2 |
| Improved forest plantations | 0.5 | 204 | |
| **Agriculture and Grasslands** | | | |
| Biochar | 1.7 | 2000–3000 | |
| Conservation agriculture | 0.8 | 750–2000 | |
| Grazing—Optimal intensity | 0.4 | 500–2000 | 2, 3 |
| Cropland management | 1.5 | 750–2000 | |
| Rice management | 0.3 | 20–50 | |
| Enhanced root phenotypes | 0.1 | 1000–2000 | |
| **Wetlands** | | | |
| Restored histosols | 1.3 | 10–15 | 2, 3 |

[1] Siry et al., 2005
[2] Griscom et al., 2017
[3] Paustian et al., 2016

than afforestation/reforestation, and converting grasslands to forest may yield less net SOC storage than converting cropland to forest (Li et al., 2012; Bárcena et al., 2014). Soil restoration, specifically for wetlands, has the potential to return these environments to a net C sink (Table 1; Waddington et al., 2010) and represents a cost-efficient mitigation strategy—projected to cost ~US$20 per Mg of sequestered C (Humpenöder et al., 2020).

Regenerative agriculture (RA) also holds a substantial role in attaining negative carbon emissions from rangeland and agricultural soils (Fig. 2; Table 1). RA is a set of locally adapted land practices that minimize soil disturbance (e.g., no-till, minimum tillage, cover cropping) and losses (e.g., erosion, degradation), while self-sustaining its ecosystem services (e.g., productivity, biodiversity; Gonzalez-Sanchez et al., 2015) using agroecology-based theory and management (e.g., compost application, crop, and grazing rotation, etc.). Hence, RA promotes C sequestration and soil health while simultaneously reducing net SOC losses by providing a direct layer of protection from disturbance. Ultimately, avoiding land conversion and disturbance a priori is the most effective strategy to maintain SOC storage, as restoration of degraded lands accrues SOC slowly (Guo and Gifford, 2002). Both active and preventative restoration practices are vital in providing ecosystem service cobenefits such as water filtration and storage.

Land managers have added organic amendments to their soils since the early periods of agriculture. The addition of C-rich amendments can improve soil health via enhancing nutrients and water storage, plant productivity, microbial diversity, and soil structure (Woolf et al., 2010; Farooqi et al., 2018; Amelung et al., 2020). Studies have now documented significant, positive impacts of organic amendments that include a 2.3 Mg C $ha^{-1}$ $yr^{-1}$ increase in SOC stock in corn fields after six years of biochar amendments (Blanco-Canqui et al., 2020), and a projected SOC sequestration potential of 1.2 Mg C $ha^{-1}$ $yr^{-1}$ in croplands after application of manure, sewage sludge, or straw (Smith, 2004). In parts of the world that have large amounts of excess biomass (ex., agricultural residue, manure, forest clippings, etc.), these amendments are viable options for climate change mitigation (Fig. 2; Table 1), while at the same time replenishing C and nutrient stocks to increase the ecosystem's overall health and resilience (Koide et al., 2015).

Recent advances in plant-based strategies have also provided new insights to address net SOC loss. These strategies rely on the ability of plants to self-regulate and self-optimize resource uptake and allocation, and thus are considered cost-effective and sustainable with limited environmental footprints. Plant roots are known to be a main source of SOC (Rasse et al., 2005), and root-derived SOC is preferentially retained by minerals (Bird et al., 2008). Therefore, the introduction of roots into deep soils can enhance slow-cycling C formation (Kell, 2011; Paustian et al., 2016). However, root exudates enhance soil microbial activity and reduce SOC stock via priming (Fontaine et al., 2007; Keiluweit et al., 2015). For this reason, plant roots are considered as a double-edged sword for SOC formation (Dijkstra et al., 2021). Still, there is evidence that deeply rooting vegetation (esp. perennial grasses) can sequester C into the deep soil (Slessarev et al., 2020). Extensive root systems introduce C to the subsoil, enhancing SOC-mineral associations, aggregate protection, and reduced access to SOC by soil microbes. In this manner, rhizosphere engineering benefits overall soil health and resource use efficiency (Dessaux et al., 2016). With proper implementation, plant-based strategies can synergize with existing strategies (e.g., conservation agriculture) to promote more SOC in the long-term savings account (Fig. 2).

## CONCLUDING THOUGHTS

Soils have supported life and stored C throughout geological history. However, human civilization has spurred drastic land use changes through agriculture and other activities. Additionally, profound alteration to the global climate system has resulted from widespread fossil fuel utilization and resulting greenhouse gas emissions. As we apply sophisticated models and propose novel technologies for understanding and addressing anthropogenic climate change, a piece of the solution is found in the soil. Natural climate change solutions involving soil health are not only cost effective, but also non-negotiable, because they are key for securing the food, fuel, and fiber necessary for an ever-increasing human population. Earth scientists, land managers, and policy makers must collaborate to continue "spending" SOC while "investing" in SOC to increase its retention in the soil and maximize its ability to support life. It's a win-win climate solution that's right beneath our feet. Let's keep it there.

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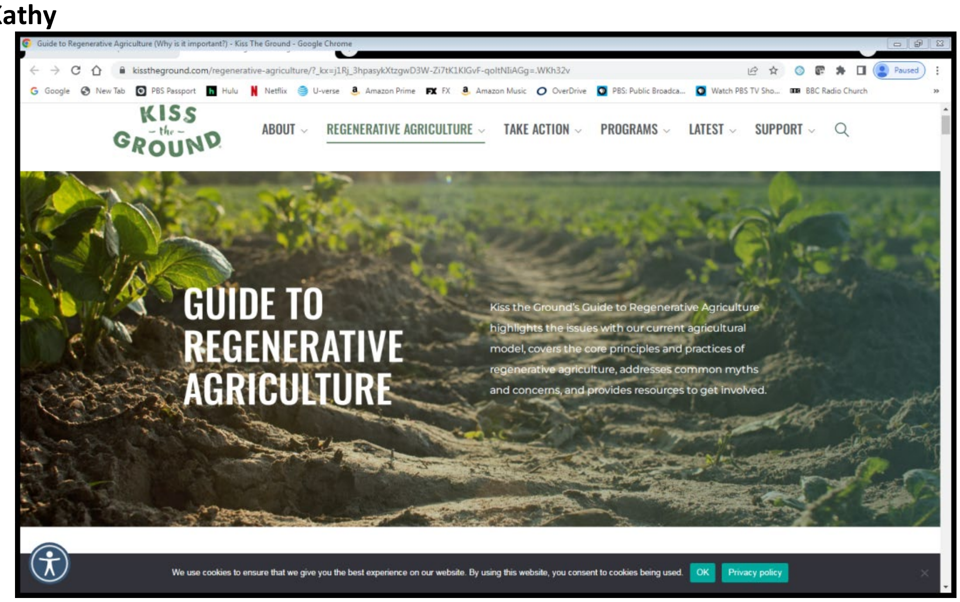
**Also from Kathy**



Here is the website link to Kiss the Ground. A wonderful video, if you have not seen it yet; and an update on their activities.
**https://kisstheground.com/regenerative-agriculture/?_kx=j1Rj_3hpasykXtzgwD3W-Zi7tK1KlGvF-qoltNIiAGg=.WKh32v**

That's all I have been able to find that people sent to me to include in this newsletter. If you sent me something and I missed it, accept my apologies and send it again to AOPeditor2020@gmail.com so it does not get lost in my normal work email site. Thanks again for all the contributions.